# Manning and Automation of Naval Surface Combatants: A Functional Allocation Approach Using Axiomatic Design Theory

by
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B.S.E. (M.E.), University of Michigan (1991)
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Department of Mechanical Engineering
in partial fulfillment of the requirements for the degrees of
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and
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at the
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June 2000



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# Manning and Automation of Naval Surface Combatants: A Functional Allocation Approach Using Axiomatic Design Theory

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## Abstract

The design of ships is an inherently complex process. This complexity is significantly increased when the particular ship being designed is a naval surface combatant. The ship design process is traditionally viewed as a highly coupled collection of interrelated physical attributes often determined in an *ad hoc* fashion. Therefore, lack of understanding and documenting the design progression frequently necessitates modification of a completely developed, functionally acceptable portion of the ship because of its undesirable effect on other functionally unrelated parameters.

A methodology based on axiomatic design principles that strives to eliminate the currently accepted iterative nature of concept level ship design is proposed. Specifically, the hierarchical decomposition of a naval surface combatant based on functional requirements mapped into physical design parameters reveals physical couplings. Studying the design at each level of the hierarchy determines the logical order to fulfill each requirement such that these couplings do not adversely impact the design progression. By implementing this methodical approach, the ship design process follows a repeatable structured format in which functional relationships between physical parameters are mapped, documented, and controlled.

Since functional design is the key to this methodology, it is extended to assist designers with assigning tasks between shipboard personnel and automated machines. With this proposed approach, functional allocation is not only possible, but also the overall ship effect of each manning and automation decision is readily determined. A case study demonstrating this point is presented.

Thesis Supervisor: Clifford A. Whitcomb
Title: Associate Professor of Naval Construction and Engineering

Thesis Supervisor: Nam P. Suh
Title: The Ralph E. and Eloise F. Cross Professor of Manufacturing

To my wife Susie and our son Jason.

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# Chapter 1

# Background

The design of ships is an inherently complex process. This complexity is significantly increased when the particular ship being designed is a naval surface combatant (warship). In this case, the designer must not only address the factors common to all seagoing vessels such as hull form, propulsion, and maneuverability, but the choice and placement of sophisticated weapons systems and sensors must also be considered. For the purposes of this study, the word ship implies naval surface combatant.

## 1.1 Motivation

The current method of designing naval surface combatants is not an exact science. Current practice dictates the design of several individual attributes which are then integrated to define the total ship concept. More often than not, extensive re-design of several of these attributes is necessary to achieve a realizable ship. Stated specifically, the current "art" of naval warship design is an iterative procedure. An efficient manner of completing the ship design process based on scientific-based reasoning is either not properly developed and documented, or totally nonexistent.

Attempting to reduce life cycle costs and limit the number of personnel placed in harm's way, the U.S. Navy plans to reduce the manning on warships. As personnel are removed, the functions traditionally performed by them must be accomplished in such a way as not to overtask the remaining personnel. By incorporating automated machines as an integral part

of the design, the ship's warfighting capability is not degraded when implementing the reduced manning philosophy. Specific functions require allocation between automated machines and the remaining personnel. A rigorous method of identifying all pertinent functions and determining the optimum combination of manning and automation is desired to replace the iterative methods currently in place.

## 1.2 Objectives

This study focuses on two specific areas, the ship design process and the allocation of shipboard functions between men[1] and machines. The following lists the objectives pertinent to each area.

Ship Design Process:

1. Model the current iterative nature of ship design for comparison with the proposed method.
2. Determine an efficient way to sequence the ship design process by eliminating iteration to the largest extent possible.
3. Accomplish all required iteration (if any remains) in a structured repeatable fashion.

Shipboard Functional Allocation Process:

1. Develop a detailed method to identify all necessary shipboard functions.
2. Create a framework in which a rigorous approach to allocate shipboard functions between men and machines can be employed (whenever possible).
3. Determine the overall impact on the resulting ship caused by manning and automation decisions using a total ownership cost basis.

The procedures utilized to attain each respective goal are introduced and discussed when appropriate. The development of an efficient ship design methodology leads naturally into the manning and automation analysis.

[1]U.S. Navy manning policy assigns "mixed gender crews," that is crews comprised of both men and women, to surface combatants. For simplicity and consistency, the male gender is used throughout this document.

## 1.3 Existing Ship Design Methodologies

The ship design process is traditionally viewed as a highly coupled collection of interrelated physical attributes. That is, certain physical aspects of the design directly impact other physical aspects. Therefore, once an aspect is fully developed, it often requires modification based on its relationship with other functionally unrelated parameters. This philosophy is extensively discussed in the open literature, for example Brown [5].

Current design of naval surface combatants is accomplished using an iterative process commonly referred to as "The Design Spiral." Evans introduced this visual model of the ship design process [9]. Since its introduction, several variations have been developed. The spiral itself is consistent between all variations, but the"spokes" defining each aspect of the design differs somewhat from version to version. The version used to instruct students of naval architecture at the Massachusetts Institute of Technology (MIT) is shown in Figure 1-1.

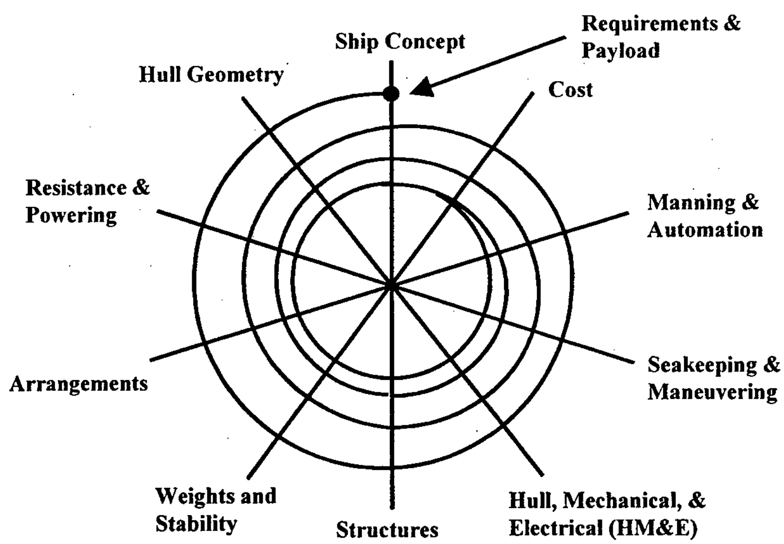



Figure 1-1: MIT Design Spiral

The spiral's spokes represent the set of all major areas that must be addressed throughout the design process to completely define the ship. The spiral itself depicts the current practice of independently developing each required parameter in a sequential manner, evaluating the

relationship between design attributes, iterating to resolve conflicts, and repeating the evaluation/iteration process until all conflicts are resolved. Thus, following each successive iteration, the design progresses closer and closer to the spiral's center until convergence is attained at a constant radius from the center.

Methods to expand the usefulness of the design spiral have been developed. Andrews added the factor of time to the model [2]. The essential concept remains the same, but the visual representation moved into three dimensions. The added third dimension represents time. Figure 1-2 is the resulting cone shaped model. The design progresses through time by "cork-screwing" down the cone following a helical path. A cross section of the cone, essentially a spiral, represents a snapshot of the design process at a given instance. Design convergence is achieved at the cone's apex.

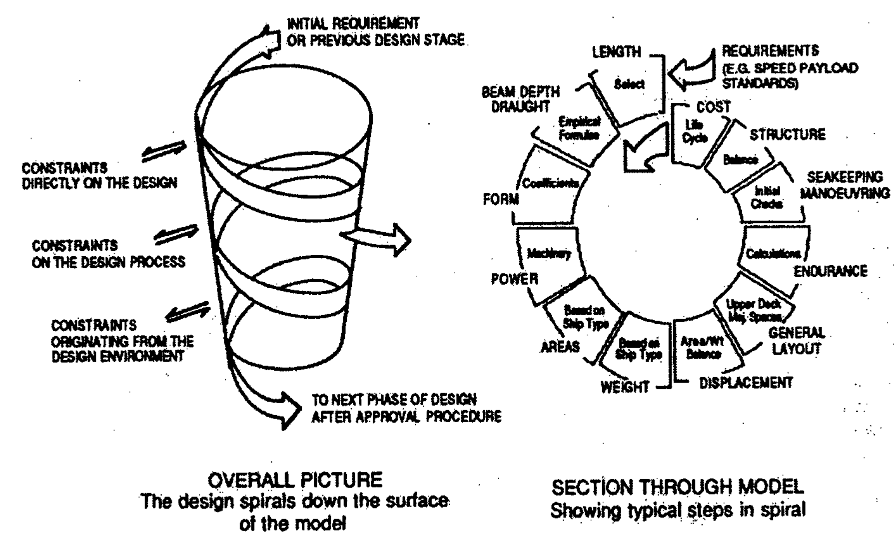



Figure 1-2: Enhanced Design Spiral [2]

Mistree, et al. recognized limitations of the spiral methods. Specifically, the inadequate addressing of concurrent engineering practices and life cycle concerns. Their proposed solution to remedy these shortfalls is Decision-Based Design for the design of ships [13]. This method divides the design process into subproblems that are solved in hierarchical order. The solutions to these subproblems must then be synthesized resulting in the overall design. Once again, compromise is necessary once a portion of the design is complete. This method is also highly

dependent on the use of computer software to achieve converged synthesis.

## 1.4 MIT XIII-A Ship Synthesis Model

The MIT XIII-A[2] Ship Synthesis Model, simply called "The Math Model", is used for concept level design of monohull surface combatants. The model was first developed by Reed in 1976 using two earlier codes, DD07 and CODESHIP, as its basis. The model has been revised and improved by a long series of naval officer students and faculty over the past two decades. The current version is more consistent with the Naval Surface Warfare Center's ASSET[3] design tool regarding the regression-based equations for weight, area, and electric power. The model performs all necessary calculations using commercially available software packages, either MathSoft, Inc's Mathcad or Microsoft's Excel. Appendix A contains the current Mathcad version of the math model. This model is evaluated in detail to gain an appreciation for the current iterative ship design method.

### 1.4.1 Math Model Overview

The math model is a parametric design tool. Parametric models link gross parameters to more detailed characteristics through regression analyses, trend analyses, and ratiocination. Some of the parametrics used to generate the model were derived from the standard U.S. naval surface vessel design lanes [16]. Since parametric based models are limited to the range of data analyzed, significant deviations from the established design lanes degrade the fidelity of the resulting concept design. The math model level of fidelity is high for ship designs with characteristics similar to existing ships, i.e. evolutionary ships. Likewise, the math model level of fidelity is low for revolutionary ship designs.

Given an extensive set of gross design parameters and a specific mission payload (weapons system configuration), the math model provides the designer a means to balance a ship in six aspects: weight, propulsion power, electrical power, volume, area, and transverse intact

[2]MIT XIII-A is the Massachusetts Institute of Technology's Naval Construction and Engineering Program. XIII signifies the Ocean Engineering Department. Course XIII-A primarily educates active duty naval officer students in a broad spectrum of marine related subjects and their applications.

[3]Advanced Surface Ship Evaluation Tool

stability. The model also incorporates a weight-based cost model to calculate the initial acquisition cost and life cycle cost of a ship class. The sum of these two costs defines a program's total ownership cost (TOC). Figure 1-3 shows the basic iterative process followed to achieve design convergence.

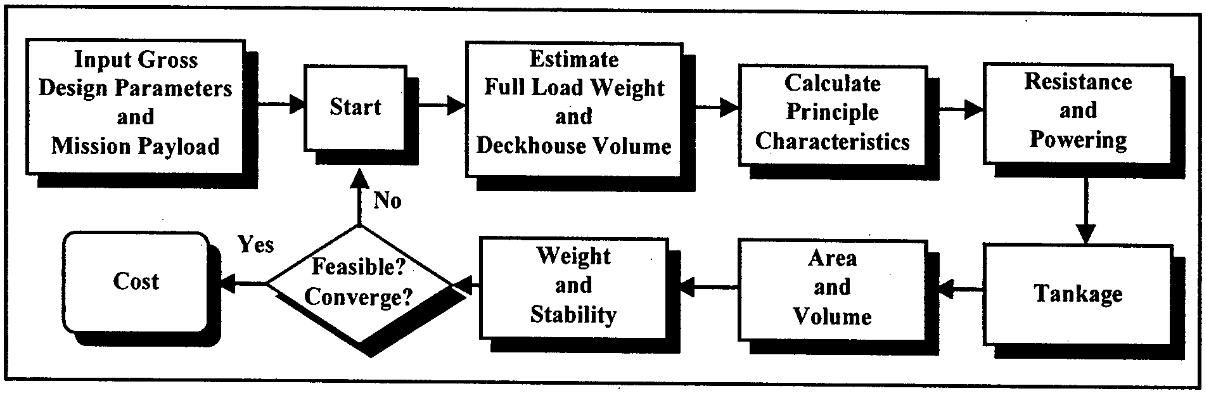



Figure 1-3: Math Model Process

The model does not conduct a longitudinal weight balance, nor does it consider any other important naval ship design aspects such as seakeeping, maneuverability, structural strength, hull subdivision, and damaged stability. These factors could be incorporated to enhance the model's capability with significant effort. Modifying the math model is not within the scope of this study. Therefore, only the above mentioned six aspects along with TOC represent the spokes of a simplified design spiral.

Essentially, this tool gives a first order approximation of a concept's feasibility. If the design can not be balanced with the parameters input, iteration is required to achieve a balanced design. The model does not automatically balance the ship by iterating the necessary parameters, but rather this iteration is accomplished manually. In other words, the designer must strategically vary the parameters suspected to cause design convergence and then check the result of each successive variation. Through experience, the designer's intuition improves and the number of required iterations decreases. But, the iterative nature of this often time consuming manual balancing process is essentially *ad hoc.*

Typically, several iterations are required to balance a ship in the six stated areas. The balanced design does not necessarily incorporate all the attributes envisioned by the designer.

For example, the final synthesized design may be longer or shorter than originally desired, have a wider or narrower beam than first envisioned, or have a larger or smaller displacement than initially conceptualized. The final balanced math model level of fidelity ship produces a reasonable starting point to begin feasibility level design. Once the gross characteristics of a design are determined with the math model, more detailed analyses can proceed using more sophisticated design tools.

### 1.4.2 Model Coupling Analysis

The math model contains numerous direct input parameters and equations. Many of the direct inputs and equation outputs affect multiple aspects of the overall design. Therefore, varying a single parameter may significantly alter the respective design. The designer must understand the possible ramifications each parameter poses on the overall conceptual design to totally control the characteristics and performance of the resulting ship. A procedure to analyze these interrelationships is desired.

One available means to investigate the parameter interrelationships, or couplings, is the design structure matrix (DSM). DSM analysis software tools, such as the Design Manager's Aid To Intelligent Decomposition With A Genetic Algorithm (DeMAID/GA) and PSM32: Problem Solving Matrix, currently exist. A discussion of the DSM as evaluated by DeMAID/GA is given as a possible way to capture the model couplings. The ultimate goal of the DSM process is to reorder the pertinent design tasks, in this case, the model's equations, to minimize feedback couplings. An entering understanding states it may not be possible to eliminate all identified feedback couplings by applying the DSM methodology. An overview of the process is presented strictly as an alternate design approach without conducting a thorough analysis. Therefore, the discussion is purely based on speculation and used only as background information.

#### Design Structure Matrix

The design structure matrix (DSM) is a management tool traditionally used to visualize the interactions between the various facets of the design process [17]. The overall design process is broken up into individual processes represented as modules. Modules require inputs from other modules and likewise output information required by other modules. The DSM captures

these input/output relationships.

Figure 1-4 illustrates a typical DSM. The numbered boxes on the diagonal represent the processes. The horizontal lines exiting the numbered boxes indicate output from each particular numbered process. The vertical lines entering each numbered box indicate inputs into the particular modules. Finally, the small squares at the intersection of each horizontal and vertical line represent couplings between the respective two processes.

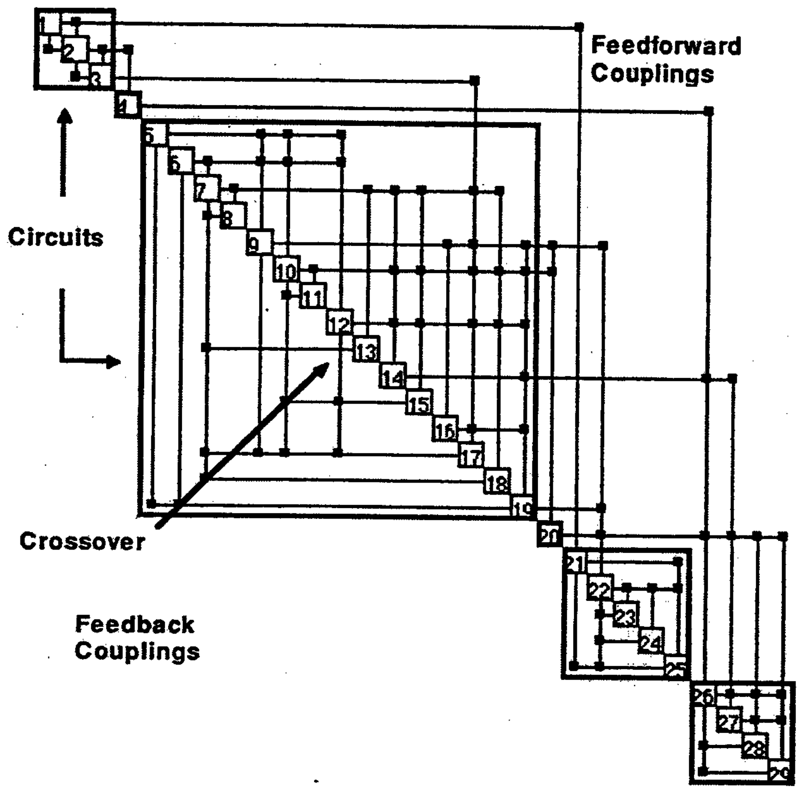



Figure 1-4: Design Structure Matrix [15]

Couplings occurring in the upper triangle are feedforward. Similarly, couplings occurring in the lower triangle are feedback. It is worth noting that some DSM researchers and practitioners use the opposite convention for feedforward and feedback couplings. Following this opposite convention, couplings occurring in the upper triangle are feedback and couplings occurring in the lower triangle are feedforward[4].

[4]PSM32: Problem Solving Matrix uses this convention.

Feedforward couplings are desirable since the required input to a process is determined prior to its use. Conversely, feedback couplings are not desirable because the input is required before actual value determination. Therefore, an estimation of the required value must be initially input. Since this initial input is only a 'best guess,' iteration is required to resolve the resulting discrepancies as further information is gained. An iterative subcycle exists because all subsequent processes relying on the subject input value must be reevaluated with successive refinement.

The principle of the DSM is mentioned because it may be used to better understand and visualize the math model's iterative design process when considering each equation used by the math model a module. Numerous directly input parameters are also used by the math model. These parameters do not contribute to the iterative nature of the design tool since they are entered at any time prior to their required usage and require no input from the modules. These numerous direct inputs are used to initialize the design process.

The relationships between the modules are determined by evaluating the equations that are dependent on the resulting output of each particular equation. The output of the equations that depend solely on initial input parameters are viewed as initialization parameters. Additionally, several equations within the math model are used specifically to verify design convergence. The outputs of these equations are not used as inputs to any other equation and are thus considered the goal of the design process. Including the design goal (convergence in all considered aspects) as a single equation, approximately 240 equations comprise the math model.

### DeMAID/GA

DeMAID/GA [15] is a design tool created within the National Aeronautics and Space Administration (NASA). This software package consists of two portions, the DeMAID portion and the GA portion. Each portion provides specific functionalities pertinent to the DSM analysis.

The DeMAID portion generates design structure matrices and evaluates design processes within the DSM framework. It provides a great benefit to the designer by determining the optimum ordering of the design tasks. In this context, optimum refers to an ordering which either eliminates iteration (feedback couplings) altogether, or minimizes iteration by identifying logical iterative subcycles called circuits.

The GA portion enhances the DeMAID portion by ordering the processes within each circuit in the most efficient manner based on cost, time, and iteration requirements. Iteration requirements refer to the number of iterations required for design convergence. The GA also minimizes crossovers. Crossovers occur when feedback from one process crosses that of another process without the exchange of information. Crossovers obscure straightforward convergence of the design process. Therefore, they are eliminated whenever possible,

To conduct an analysis of the math model, the modules are input into the software package in their original order. Since the modules consist only of equations, the considerations of cost and time are not germane. Therefore, the cost function is not activated and the time to complete each module is a constant value. At this point, the current iterative process is accurately represented. Then, DeMAID/GA optimally rearranges the modules minimizing feedback couplings and creating iterative subcycle. This concludes a potential approach to evaluate the MIT XIII-A Ship Synthesis Model using the design structure matrix and the utility of DeMAID/GA.

## 1.5 Summary

Iteration is an accepted part of conceptual ship design. Traditional naval architects practice the art of iteration by utilizing "The Design Spiral" without postulating a more controlled, less *ad hoc* design methodology. DSM techniques offer potential. By ordering the math model equations to reflect a revised DSM manipulated by DeMAID/GA or a similar tool, the designer more clearly understands the iteration process. Covergence of each iterative subcycle must be attained before commencing design of the next subcycle. Pure speculation states, the electrical system must be designed before ever considering design of the propulsion system, etc. Visually, this speculative design process is conceptually represented as the series progression of design spirals leading to final convergence shown in Figure 1-5.

The designer's original vision is not necessarily guaranteed using this reordered DSM method. But, this method affords the opportunity to revise the concept at specific incremental steps throughout the design process. The verbatim following of this logical design progression ensures the synthesis of each conceptual designs in the same manner; the *ad hoc* nature of the ship

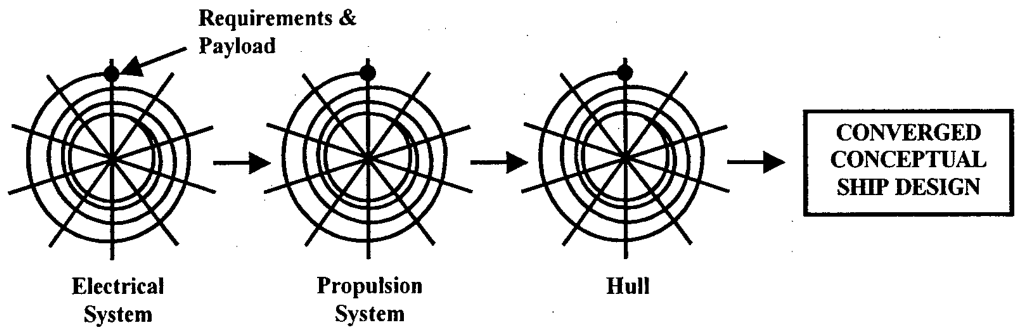



Figure 1-5: Conceptual Iterative Subcycles - A Possibility

design process disappears. Thus, one of the main shortfalls of current ship design methodology is eliminated.

The next step in the study explores the feasibility of eliminating all iterative subcycles. In order to eliminate all iterations, the ship design process must be fundamentally altered. In other words, the approach to ship design must be viewed differently. The knowledge gained from the preceding analysis is a solid foundation to begin the next portion of this study, the modification of the ship design process. The math model equations are retained for use in the proposed design approach because they represent a sound basis to define a concept level ship's characteristics and physics-based performance.

# Chapter 2

# The Axiomatic Approach to Design

Current ship design methods require the use of an iteration process. The iteration process necessarily dictates the modification of each parameter conflicting with one or more other parameters until agreement in all aspects is reached. Therefore, the final synthesized design is a variation of the designer's vision often arrived upon using trial-and-error methods. This process is rarely accomplished in the same sequential manner, making it *ad hoc.* By applying axiomatic design [18], [20] techniques, the need to iterate is minimized, or eliminated altogether. If iteration is required, it is accomplished in a highly ordered, repeatable fashion.

## 2.1 Analysis Overview

"Analysis" refers to the investigation of applying axiomatic design principles to the ship design process. "Evaluation" and "study" are used synonymously with "analysis" throughout.

The ultimate goal of axiomatic design is the formulation of scientific-based, non-iterative design solutions. One of the salient properties of axiomatic design is that it empowers the designer to exercise creative thinking. By exercising creativity, the designer may envision innovative solutions to attain the underlying goal of axiomatic design, the efficient solution to design problems. Pure axiomatic design takes place in a "solution neutral" environment. It is often difficult for the designer to remain completely "solution neutral" because all existing design solutions must necessarily be disregarded. In this environment, innovative solutions are conceived and then physically realized.

As eluded to above, to truly apply axiomatic design methods, the design process must start and progress in a "solution neutral" environment. For this study, the well established notion of how a ship exists at the basic level is maintained. Because of this entering argument, the primary goal is not to completely redesign a new system to fulfill naval functions using axiomatic design. Rather, the goal is to explore the feasibility of using axiomatic design principles, specifically the Independence Axiom, to define an efficient way to structure the ship design process[1]. This is achieved by determining the proper sequencing for the completion of each design task such that each parameter has minimal impact on all other parameters. The result is the elimination or minimization of the iteration process. Thus, the true vision of the designer is attained, or the iteration process is completely controlled by using a methodical, repeatable approach.

At various points in this analysis, true axiomatic design is applied using non-traditional thinking to propose innovative solutions to satisfy specific functions. These creative solutions are only proposed when considered reasonably achievable and physically quantifiable. Proposed innovative solutions may be devised during the analysis procedure, while others are documented conceptual ideas conceived by other sources.

## 2.2 Axiomatic Design Fundamentals

The axiomatic design framework consists of four separate domains, the customer domain, the functional domain, the physical domain, and the process domain. A specified vector type characterizes each domain as shown in Figure 2-1. Mapping enables the designer to logically progress through the design process by first determining **what** is required in each domain, and then specifying **how** these requirements are satisfied in the next successive domain. Mapping between the domains is done using design matrices. The entire process advances by "zigzagging" between adjacent domains, thereby producing a hierarchial decomposition as the design is defined in increasing detail.

Brown and Thomas introduced axiomatic design principles to propose a naval ship design process framework [4]. Their domains are tailored to reflect concept level ship design. Partic-

[1] The foundation of axiomatic design is two axioms: the Independence Axiom and the Information Axiom. The Information Axiom is neither discussed, nor utilized in this study.

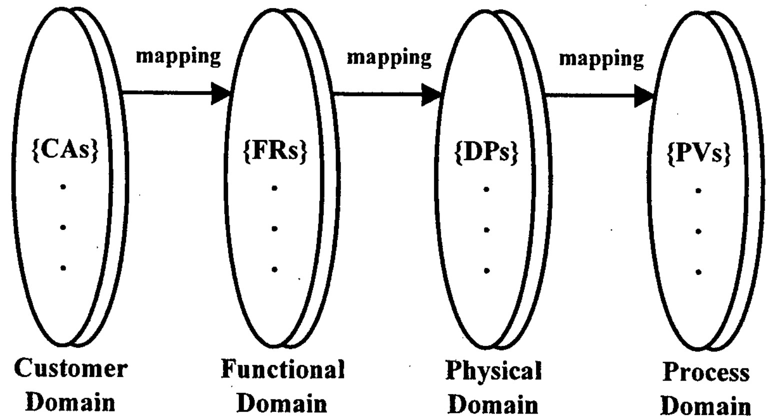



Figure 2-1: Design Domains including Characteristic Vectors

ularly, the customer domain is referred to as the mission domain. This reasonable modification is discussed in the following subsection. Both the mapping process and design decomposition process are discussed, but neither are fully developed. Specifically, the use of design matrices is not implemented (or mentioned) and decomposition is not carried out explicitly with the "zigzagging" process. A notional top level design hierarchy in all domains is given only as an overview.

### 2.2.1 The Role of the Customer Domain and the Process Domain in the Ship Design Process

Since this study initially evaluates a non-specific design, customer attributes (CAs) in the customer domain are generalized. The formulation of specific customer requirements begins with the exploratory mission analysis process. The key result of such an exploration is a detailed Mission Needs Statement (MNS) which outlines all facets of the mission that must be accomplished. The accomplishment of the stated mission is the reason for beginning the conceptual design process.

When viewing the ship design process in this mission driven context, the customer domain may also be called the mission domain. Once the mission requirements are clearly defined, an analysis of alternatives (AOA) determines the best means of performing the mission. In this particular case, the AOA selects a new class of surface ships. Other methods of accomplishing

the same mission include aircraft, submarines, ground troops, change in current tactics, etc. Therefore, the MNS is the primary means to determine the CAs requiring mapping into the functional domain. In turn, the CAs determine the functional requirements (FRs) and the overall constraints placed on the design process. Constraints limit the designer's available choices of design parameters (DPs). Figure 2-2 illustrates the progression from initial exploratory mission analysis to conceptual physical design.

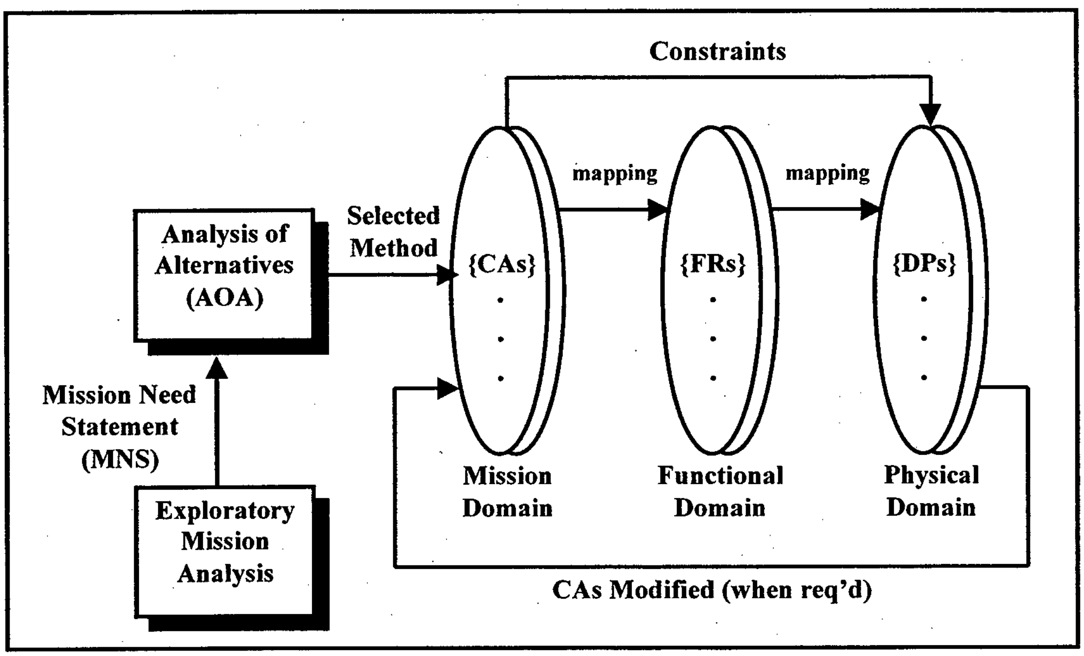



Figure 2-2: Mission Driven Design Progression

The current practice used to evaluate the effectiveness of a naval combatant is based on its ability to carry out the specific missions it was designed to accomplish according to the MNS. Therefore, effectiveness is measured in a context where the ship itself is viewed as a component, for instance during carrier battle group or amphibious operations, referred to as a supersystem [12], or a system-of-systems. Typically, tradeoff studies are conducted to determine the optimum combination of physical attributes (weapons payload, propulsion plant type, storage capacity, etc.). These studies solidify the customer attributes.

In the axiomatic approach to design framework, effectiveness of a design is based on its ability to satisfy the specified functional requirements. Once the best conceptual design is

determined in the system-of-systems framework, the customer attributes are mapped into the functional domain. Upon entering the functional domain, axiomatic design is the method used to ensure maximum mission effectiveness.

For the purpose of the ensuing evaluation, a formal mapping from the customer domain into the functional domain is not accomplished. Formal mapping of CAs into FRs is often difficult because the customer is often unable to precisely outline the desired specifications. For this reason, after a physical conceptual design materializes it must be presented to the customer. If the proposed design does not meet the expected performance, the CAs are modified causing the design goals to be re-defined. Figure 2-2 also illustrates this phenomenon.

Certain attributes such as sustained speed (the maximum speed a ship can attain for an extended transit), endurance range (the range a ship can travel without requiring additional fuel), and stores period (the length of time a ship can operate independently without requiring additional provisions, repair parts, etc.) are incorporated into the design directly as FRs. Other pertinent customer attributes, such as initial acquisition cost and daily operating cost, are input as design constraints. For the initial framework development, the values for these customer derived parameters are omitted. They are easily input when conducting specific case analysis.

This study also does not include the process domain. By use of a design matrix DPs in the physical domain are fulfilled by process variables (PVs) in the process domain. Process variables (also referred to as realization variables (RVs)) are the production and manufacturing resources needed to physically construct the required design parameters. In the context of ship design, the production tools and techniques used to construct each portion of the ship comprise the possible PVs.

Collectively, these production tools and techniques are considered when creating a ship's build strategy. Production assets and methods are specific to each contracted shipyard. Therefore, a shipyard's capabilities constrain the designer's choice of available PVs. Since neither an evaluation of a specific shipyard, nor a study of the ship production process is desired, the process domain is not addressed.

### 2.2.2 Mapping from the Functional Domain to the Physical Domain and Design Decomposition

This study focuses on the functional domain and the physical domain. Specifically, "what functional requirements must be provided" and "how is each specified requirement fulfilled by use of design parameters." Equation 2.1 expresses the design process in vector format. Equation 2.2 represents the individual equations comprising the design process. The entire analysis is accomplished by "zigzagging" between these two domains, as the design is refined through decomposition.

$$\{\mathbf{FR}\} = [\mathbf{A}]\{\mathbf{DP}\} \tag{2.1}$$

$$\{\mathbf{FR}\} = \text{functional requirement vector}$$

$$\{\mathbf{DP}\} = \text{design parameter vector}$$

$$[\mathbf{A}] = \text{design matrix}$$

$$FR_i = \sum_j A_{ij} DP_j \tag{2.2}$$

When following standard practice to initially evaluate a design, $X$'s and $O$'s populate all design matrix elements ($A_{ij}$). These symbols represent the interaction between FRs and DPs. An $X$ in position $ij$ signifies $DP_j$ effects $FR_i$. Similarly, an $O$ in position $ij$ signifies $DP_j$ does not effect $FR_i$. Equation 2.3 provides the mathematical definition of the design matrix elements.

$$A_{ij} = \partial FR_i / \partial DP_j \tag{2.3}$$

If $DP_j$ never changes in such a way as to influence $FR_i$, $A_{ij}$ is represented by an $O$. $A_{ij}$ may be either constant or varying throughout the design space. If $A_{ij}$ is not a constant value, it must be evaluated at specific design points in the physical domain. Additionally, $FR_i$ does not always vary linearly with $DP_j$. In these cases, as $DP_j$ changes, the value of $FR_i$ either increases or decreases in a nonlinear manner. Therefore, $A_{ij}$ varies with both $FR_i$ and $DP_j$.

For this study, all evaluations occur within the linear bounds of a design point.

Figure 2-3 shows an arbitrary functional to physical domain mapping applying these definitions. Equations 2.4 list these sample design equations in simultaneous equation format for further clarification. Note that all $X$'s are replaced by their respective matrix element designation in the simultaneous equations. For detailed analysis, the initial design equations characterized by $X$'s and $O$'s are updated at the appropriate level of decomposition by replacing each $X$ with a quantifiable engineering expression.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ \vdots \\ FR_i \end{Bmatrix} = \begin{bmatrix} X & O & X & \cdots & O \\ X & X & O & \cdots & O \\ X & X & X & \cdots & O \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X & X & X & \cdots & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ \vdots \\ DP_j \end{Bmatrix}$$

Figure 2-3: Sample Design Equations

$$\begin{aligned} FR_1 &= A_{11}DP_1 + A_{13}DP_3 + ... \\ FR_2 &= A_{21}DP_1 + A_{22}DP_2 + ... \\ FR_3 &= A_{31}DP_1 + A_{32}DP_2 + A_{33}DP_3 + ... \\ FR_i &= A_{i1}DP_1 + A_{i2}DP_2 + A_{i3}DP_3 + ... + A_{ij}DP_j \end{aligned} \tag{2.4}$$

The "zigzagging" process enables the designer to logically decompose the design, thereby developing FR and DP hierarchies. Figure 2-4 illustrates this process. First, the designer selects a DP to satisfy a particular FR. Then a determination regarding further decomposition is made. If the selected DP is a well established component or system which does not require re-design, the decomposition stops. For example, a naval architect seldom designs the prime mover which propels the ship. Instead, the appropriate engine is selected from an existing marine propulsion database. In this case, decomposition ceases once the naval architect selects the desired engine type.

On the other hand, if the chosen DP is not a well understood legacy component or system, decomposition is required. The designer decomposes the DP by determining the FRs it fulfills. Then, each of these FRs is satisfied with a suitable DP. Once again, a determination regarding the status of the lower level DP decomposition is made using the stated criteria. The designer "zigzags" between the two domains in this fashion until all the lowest level DPs do not require re-design. This lowest lower of decomposition is referred to as the *leaf level.* The DPs at this level are called *leaf nodes.*

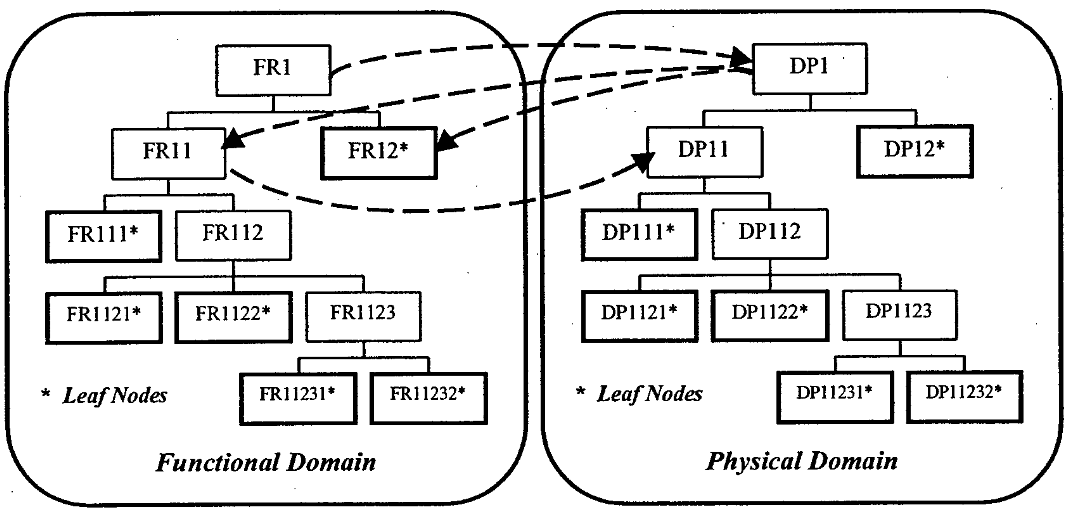



Figure 2-4: "Zigzagging" between Domains resulting in Hierarchial Design Decomposition

The standard practice of tracking the design hierarchy is to use a numerical accounting scheme. Each highest level, or parent, FR/DP pair is given a sequentially increasing number designation (1, 2, 3, ...). At the next level of decomposition, the first child level, a sequentially increasing number is added to the right of the parent designation. For this study, a decimal point separates these two fields (for example, 1.1, 1.2, 1.3, ... or 2.1, 2.2, 2.3, ...). If further decomposition is necessary, this procedure is again followed and a sequentially increasing number is added to the right of another decimal point (for example, 1.1.1, 1.1.2, 1.1.3, ...). In this manner, the design grows as *branches* until reaching the leaf level. The detail of each branch, that is the level of decomposition, varies depending on the DPs selected.

As stated earlier, the ship is currently thought of as many coupled physical attributes. In

the axiomatic approach to design framework, this view must be discarded. The ship must initially be evaluated in the functional domain instead of the physical domain. Once the top-level FRs are determined, top-level DPs are developed to satisfy the FRs. The design process continues with decomposition of FRs until a complete solution is attained. Throughout the decomposition process, DPs are developed to satisfy FRs at descending levels of complexity. The design solution is complete when the chosen DPs exist at the *leaf level.*

A good design maintains the independence of the functional requirements according to the Independence Axiom. According to axiomatic design theory, the design process does not continue to the next level of decomposition until the Independence Axiom is satisfied. Independence is achieved by either an uncoupled or decoupled design. An uncoupled design is one in which only one DP satisfies each FR. A diagonal design matrix characterizes this type of design. A decoupled design is one in which the independence of functional requirements is satisfied if and only if the DPs are changed in the proper sequence. A triangular (upper or lower) design matrix characterizes this type of design.

A coupled design does not satisfy the Independence Axiom. This type of design signifies the need for iteration because successive DPs are not necessarily fixed as FRs are sequentially satisfied. In other words, a DP may require modification to satisfy one or more additional FRs. Once this modification occurs, the fulfillment of the original FR (in part by the subject DP) must again be verified. If fulfillment is not achieved, the subject DP must once again be altered initiating the iteration process. A design matrix with elements populating both sides of the diagonal characterizes a coupled design.

Certain functional requirements of ships are inherently coupled (i.e., operate on surface of the water and move through the water). Therefore, developing a decoupled design is sought. A decoupled design allows the designer to concentrate all efforts in a logical sequence thereby eliminating the iteration process. Once a portion of the design is complete, it theoretically does not require further modification upon completion of another aspect of the design.

The most salient benefits of achieving a decoupled design are seen after the design is complete. With a decoupled design, the effect that an engineering change order (ECO) has on shipboard systems not directly related to the change is more readily known. Technologies to improve the warfighting capabilities of modern naval surface combatants are continuously un-

der development. This is especially true for applications involving computer microprocessing technology. Therefore, it is often desirable to install these emerging technologies onto the ship once they are fully developed. This happens at any conceivable point throughout the ship's life cycle. A decoupled design allows the overall effect these new technologies have on other systems to be determined prior to insertion. Therefore, modifications enhancing the ship are less costly to implement at any stage of commissioned life.

## 2.3 Summary

Currently, naval architects consider iteration a fact of waterborne vessel design. The amount of required iteration increases when design teams are involved, which is normally the case. Typically, team members work independently on a particular facet of the design with only limited knowledge of the advancing designs of other facets. Then, during team discussions, conflicts arise between the independently designed systems. These conflicts must be resolved through redesign until all functionally satisfactory aspects of the proposed ship design physically agreement. Therefore, both the 'design spiral' methodology and mentality are perpetuated.

By applying axiomatic design techniques to the concept level ship design process, it is postulated that the dependence on iteration will be broken. The best case scenario eliminates iteration altogether. But, at the very least, iterate is minimized, and controlled by implementing a scientific based design sequence. Simply stated, if iteration is required, it is accomplished in a highly ordered, repeatable fashion. By following the specified design progression determined by functionally evaluating the ship design process, individual designers, and design teams working in tandem, know about potential functional couplings *a priori.*

For this study, a minimum amount of iteration is acceptable if it is determined that the Independence Axiom cannot totally be satisfied. In all cases, every attempt is made to reduce couplings. But, a violation of the physics governing the operation of ships does not occur for the sole purpose of creating a non-coupled design. In other words, "the design is what it is" unless an innovative way to fulfill the FRs in such a way that couplings disappear is devised. Couplings remaining at the end of the analysis are documented for accomplishment at specific points in the design process.

# Chapter 3

# Proposed Ship Design Methodology

Using the axiomatic design principles outlined in Chapter 2, a method to design a warship is developed. Thus, this design methodology takes place in the axiomatic approach to design (AAD) framework. As stated earlier, this analysis only loosely considers the customer (or mission) domain and essentially begins in the functional domain. In the functional domain, the functional requirements needed to sufficiently define a generic naval surface combatant are determined. Then, in the physical domain, design parameters to satisfy these FRs are selected and decomposed as necessary. The analysis progresses by "zigzagging" between the two domains to conceptually define a warship in sufficient detail. Finally, the warship design is physically realized by interjecting applicable engineering expressions wherever germane. The interjection of engineering expressions does not occur until the entire ship is defined using conceptual ($X$ and $O$) design equations.

The axiomatic design procedure defining a warship is quite involved. Because of this reality, an automated method of documenting the extensive design decomposition, numerous design equations, and governing constraints is highly desirable. A software package called Acclaro[1] is designed to meet these functions. Thus, Acclaro is used throughout this portion of the study.

[1]Acclaro Software is currently under development by Axiomatic Design Software, Inc. Beta Versions B0.5 and B0.6 assisted the author with conducting this analysis.

## 3.1 Initial Design Constraints

As in all designs, certain constraints are initially placed on the overall design. In this case, the first initial constraints become an integral part of the overall design philosophy. The first set of constraints result from the underlying motive of the Department of Defense (DoD) acquisition reform policy, ensure total ownership cost (TOC) does not exceed the mandated value. TOC includes the initial acquisition cost and the life cycle cost (calculated by multiplying the average hourly operating cost by the total operating hours). These constraints are stated as follows.

$$
\begin{aligned}
C_1 &= \text{Initial acquisition cost} \leq \$\ XXM \text{ (say, } \$\ 750M) \\
C_2 &= \text{Average hourly operating cost} \leq \$\ XX \text{ (say, } \$\ 2,600/hr)
\end{aligned}
$$

Due to the demands for accountable budgets, the current DoD acquisition strategy requires fully capable weapons systems for a reasonable cost. Each acquisition program operates on a strict budget that cannot be exceeded, currently using the cost as an independent variable (CAIV) concept [6]. This concept is synonymous with evaluating potential systems not only on their capabilities, but also on their projected costs. In some cases, the philosophy may even result in limiting or eliminating specific capabilities based on a cost-benefit analysis. In other words, designs are judged on their ability to incorporate capabilities without exceeding the applicable cost threshold. Therefore, major program managers strive to develop a design which achieves "the most bang for the buck."

By applying the principles of axiomatic design, it is reasonable to postulate that cost savings are realizable due to increased design efficiency and improved understanding of systems interrelationships. By keeping cognizant of the relevant cost constraints while developing the design solution, even greater savings are potentially achievable.

The next set of constraints result from the physics governing ship operations. The ship must operate on the water's surface. Since the combatant chosen for evaluation is a conventional monohull, it relies on buoyancy to support its weight. The hull form's displaced volume creates this buoyant force. The ship's total weight equals the weight of the hull plus the weight of all shipboard systems, equipment, stores, and personnel. The weight of the displaced volume of water (termed the full load displacement) is equal to the total weight of the ship

according to Archimedes' Principle. If the hull is shaped in such a manner that the total weight is well supported, the design is sound. If the total weight of the ship exceeds the weight of the maximum amount of water that can be displaced by the ship hull volume, the ship sinks. Since prudent naval architecture practice dictates that a surface vessel should always float, the following design constraint is imposed.

$$C_3 = \text{Full load displacement} = \text{Total weight}$$

In addition to floating, the ship must remain upright in stable equilibrium. A ship in stable equilibrium returns to its original position when heeled by an external inclining force that is applied and subsequently removed. Conversely, a ship in unstable equilibrium does not return to its original position resulting in capsizing [11]. Metacentric height ($GM$) indicates the ship's stability in an intact (non-damaged) condition. $GM$ is determined by the location of the ship's center of gravity ($G$) in relation to its metacenter ($M$). $M$ is related to hull geometry, and $G$ is determined by the vertical placement of weights on board. If $M$ is above $G$, intact stability exists. The center of buoyancy ($B$) is the geometric center of the underwater hull volume. The lowest point on the keel ($K$) is used as a datum point. Figure 3-1 illustrates all relevant parameters. A positive metacentric height ($GM > 0$ ft) is required for intact stable equilibrium. Once again, prudent naval architecture practice imposes the following constraint.

$$C_4 = \text{Ensure intact stability } (GM > 0 \text{ ft})$$

By complying with $C_4$, the ship remains upright in stable equilibrium. Even though the ship returns to its original position following a heel, does not necessarily ensure this return occurs in an acceptable manner. A measure of this response is transverse dynamic stability. A ship that returns in a noticeably slow time is said to be "tender." A ship that "snaps back" is said to be stiff. Both cases are uncomfortable for crewmembers and adversely effect shipboard evolutions. Therefore, proper transverse dynamic stability must be maintained according to $C_5$. The metacentric height to beam ($GM/B$) ratio verifies compliance with this constraint. A $GM/B$ ratio between the range of 0.090 - 0.122 is the generally acceptable design standard for monohull surface ships. Another indicator of acceptable dynamic performance is

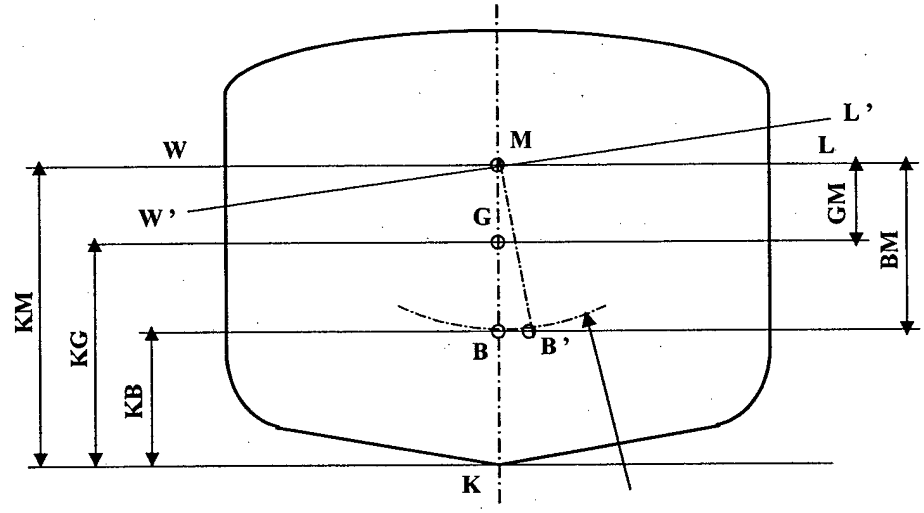



Figure 3-1: Transverse Metacentric Parameters

the ship's roll period which determines the time required to return to an upright position. The roll period affects various shipboard evolutions requiring a stable platform. These evolutions include launching and recovering helicopters and small boats. A single constraint is imposed to check transverse dynamic stability.

$$C_5 = \text{Ensure acceptable transverse dynamic stability } (0.090 \leq GM/B \leq 0.122)$$

As the ship moves through the water, resistance results. As speed (velocity) increases, so do the associated resistive forces. All resistance must be counteracted in order for the ship to continue in the desired path of motion at the desired speed. When traveling at a constant velocity, the total resistance remains constant. The means of counteracting the resistive forces is with installed propulsive power. Therefore, the ship must possess adequate propulsive power to ensure that the resistance encountered at all projected operating speeds can be equaled. Thus, the following design constraint exists.

$$C_6 = \text{Installed propulsive power} \geq \text{ Required propulsive power}$$

Numerous shipboard systems require electrical power. While conducting underway oper-

ations, the ship is an independent platform. Therefore, the ship must possess the capability of generating its own electrical power. The means of doing this is with the installed electrical system. The following constraint results to ensure the necessary systems receive a sufficient power supply.

$$C_7 = \text{Installed electrical power} \geq \text{ Required electrical power}$$

All systems designed to fulfill the functional requirements must fit within the physical confines of the hull and superstructure. This geometric consideration results in placing two additional constraints on the design process. First, all systems must fit within the total volume. Second, the components comprising these systems must fit in the available deck area in such a manner that their functionality is not hindered. Usable deck space is referred to as the arrangeable area. These constraints are stated as follows.

$$\begin{aligned} C_8 &= \text{Total available volume} \geq \text{Total required volume} \\ C_9 &= \text{Total available arrangeable area} \geq \text{Total required arrangeable area} \end{aligned}$$

The last initial constraint also affects the overall design philosophy. It arises because certain systems deployed on naval vessels are upgraded due to the long ship lifetime with respect to new technology development cycle time. Also, new systems not even conceivable during the design phase are later developed and then integrated into the existing ship to enhance its warfighting capabilities. To account for stability considerations during upgrades, design growth margins must be incorporated early in the conceptual design process. These design margins allow for the later addition of weight without adversely affecting the ship's ability to operate in a stable condition. Because additional weight is added, additional propulsion power becomes necessary. And, modified systems or components may produce additional electrical power consumption. Both power concerns require design growth margins. This constraint is stated in non-specific terms as follows.

$$C_{10} = \text{Incorporate design growth margins (weight, KG, propulsion and electrical power)}$$

With all the initial design constraints clearly outlined, the design process begins. The designer must always consider these constraints when selecting the design parameters to satisfy each functional requirement at all levels within the design hierarchy. An explanation regarding the applicability of these initial constraints to the highest level FRs is further discussed after devising the highest level design equations. Additional constraints may arise as the design process advances.

## 3.2 Highest Level Design Equations

To initiate the process of ship design in the axiomatic design framework, the highest level functional requirements common to all seagoing vessels, as well as those germane only to warships, are formulated. The six FRs listed below state the necessary requirements. The DPs selected to satisfy these FRs are also listed adjacent to their respective FR. An explanation of all FRs and DPs, as well as the design matrix relating the two domains are discussed after presentation of the design equations.

| | |
|---|---|
| $FR_1$ = Move through water | $DP_1$ = Propulsion system |
| $FR_2$ = Maintain desired course | $DP_2$ = Maneuvering and Control system |
| $FR_3$ = Neutralize enemy targets | $DP_3$ = Combat systems configuration |
| $FR_4$ = Protect from enemy attack | $DP_4$ = Countermeasures methods |
| $FR_5$ = Conduct sustained underway operations | $DP_5$ = Support / Auxiliary systems |
| $FR_6$ = Operate on surface of water | $DP_6$ = Hull form |

With the definition of the highest level FRs and DPs complete, the next step is to generate the design matrix. Following standard practice, $X$'s and $O$'s are used to populate all matrix elements ($A_{ij}$). These symbols represent the interaction between FRs and DPs. Lowercase $x$'s are also used to signify weak functional dependence. Equation 3.1 is the highest level design equations in their original form. As stated previously, the goal is to achieve a decoupled design characterized by a lower triangular design matrix. Since the initial design matrix is not triangular, the Independence Axiom is not satisfied. Before continuing with the design process, attempts must be made to achieve a decoupled design. This is possible only if logical

justifications for disregarding functional dependencies exist such that reality is not violated solely to achieve the desired end. The following assumptions represent one way, though possibly not the only way, to analyze the design matrix.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{Bmatrix} = \begin{bmatrix} X & x & O & O & O & X \\ x & X & O & O & O & x \\ X & X & X & O & O & x \\ X & X & X & X & O & X \\ X & X & O & O & X & X \\ X & X & X & X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{Bmatrix} \tag{3.1}$$

$FR_1$, move through water, is satisfied by $DP_1$, the installed propulsion system. There is also a weak correlation between $FR_1$ and $DP_2$, the ship's maneuvering and control system, since some of the maneuvering systems, such as auxiliary propulsion units (APU's) and bow thrusters, can be used to move the ship through the water. The primary function of these stated systems truly relates to maneuverability alongside a pier, and not to actual open ocean movement. Thus, the removal of the $DP_2$ dependence is justified. Therefore, an $O$ replaces the corresponding lowercase $x$.

The ability for the ship to move through the water is highly dependent on the ship's hull form, $DP_6$. Specifically, the dependence occurs because of the hull form's interaction with the water. This interaction affects the speed at which the ship travels due to hull resistance. The magnitude of resistance on the hull depends on two factors, wetted surface area and hull shape at the air-water interface or free surface. Friction drag is directly proportional to the wetted surface area and wave making (residuary) drag depends on the fullness of the hull form at the free surface.

Both of these hull related factors, wetted surface area and hull shape at the free surface, continually change with the ship's displacement. During normal operating conditions, the ship's displacement continually changes as fuel is burned, stores are consumed, and weapons are expended. In order to negate the effect of $DP_6$ on $FR_1$, the ship must operate at a constant displacement (recall the definition of $A_{ij}$ given in Equation 2.3). That is, if the ship's displacement does not change, the two important hull related parameters, and therefore the hull

resistance, remain constant. Operating at a fixed draft (the vertical distance measured from the keel to the waterline) ensures operating at a fixed displacement. This draft essentially sets the point about which all evaluation occurs, the design point. So, to justify removing the effect of $DP_6$ and replacing the respective $X$ with an $O$, an additional constraint must be imposed on the design as follows.

$$C_{11} = \text{Always operate at the design waterline (DWL)}$$

$FR_2$, maintain desired course, is achieved primarily by the ship's maneuvering and control system, $DP_2$. $DP_1$, the propulsion system, somewhat affects the ship's maneuvering characteristics. In single screw designs, unbalanced hydrodynamic forces are caused due to propeller rotation. In twin screw designs, manipulating the rotation speed and pitch of each propeller independently actually enhances maneuverability. The number of screws and the propulsion system characteristics are set when fulfilling $FR_1$. Their effect on maneuverability must be considered prior to setting $DP_2$.

The hull form, $DP_6$, may also relate to maneuverability. Certain hull features, such as bulbous bows, fin stabilizers, and skegs, cause hydrodynamic forces on the ship that affect its maneuverability. Following current warship design practice, a bulbous bow is not incorporated into the design of this generic warship, but, conventional bulbous bow-like sonar domes are frequently designed into modern warships. Sonar domes, skegs, and fin stabilizers do not technically comprise the hull form, but are rather additions to the hull form as appendages. By following this logic, an $O$ replaces the subject lowercase $x$.

$FR_3$, neutralize enemy targets, is affected by $DP_1 - DP_3$ and $DP_6$. The primary DP is $DP_3$, the combat systems configuration. In order to neutralize some enemy targets, the ship must be within the appropriate weapons range. The propulsion system ($DP_1$) allows this. Often, the target must also be positioned in a specific orientation relative to the ship. The maneuvering and control system ($DP_2$) allows this positioning. Ensuring the target is within the appropriate weapons range and acquired at the necessary relative position is not the designer's concern, but rather that of the warfighters operating the ship. Since this study investigates the design process, and not the ship's operating procedures and doctrine, both discussed $X$'s are replaced

by $O$'s.

In order to accurately track and engage enemy targets, a stable platform is required. The platform in this case is the ship's hull form ($DP_6$). In this context, stability is not related to the ship's ability to right itself once perturbed; this type of stability is assumed. In this context, stability is related to the ability of the platform supporting the weapons system sensors to prevent excessive oscillations when in a sea state. Current weapons systems technology compensates for, or damps out, almost all encountered platform oscillations. Based on the existence and incorporation of such technology, coupled with the fact that the hull form of the generic warship does not diverge from traditional surface combatant hull forms, an $O$ replaces the respective lowercase $x$.

$FR_4$, protect from enemy attack, is affected by $DP_1 - DP_4$ and $DP_6$. $DP_4$, countermeasures methods, is the principal means of providing protection from enemy attack. Countermeasures methods consist of both passive and active means of defeating enemy weapons. Passive methods include reducing the ship's radar cross section (RCS) and acoustics signature. Active methods include utilizing weapons systems designed to engage incoming enemy threats. Additionally, many of the same combat systems used to neutralize enemy targets ($DP_3$), with modifications to their engagement protocols, can also be used for ship self defense measures ($FR_4$).

The contributions of $DP_1$, $DP_2$, and $DP_6$ parallel the reasoning listed in the preceding paragraph. This reasoning allows the replacement of both $X$'s associated with $DP_1$ and $DP_2$ with $O$'s. But, the uppercase $X$ associated with $DP_6$ signifies two additional contributions to $FR_4$. First, the RCS is affected by both the above water portion of the hull and the superstructure. Because the above water portion of the hull set constant by satisfying $C_{11}$, and by making the conscious design decision to focus RCS reduction efforts on the superstructure alone, the first additional contribution from $DP_6$ is removed. Second, the extent of battle damage a ship is capable of sustaining is directly related to the hull structure. Again, by making the conscious decision to design the hull based on structural strength criteria and not deviating from established warship structural design practices, the final contribution from $DP_6$ is removed from $FR_4$. Thus, an $O$ replaces the corresponding $X$.

$FR_5$, conduct sustained underway (at sea) operations, requires $DP_1$, $DP_2$, and $DP_5$ to be fully satisfied, and is affected by $DP_6$. The primary design parameter is $DP_5$, the support

and auxiliary systems. This broadly defined DP decomposes to encompass a wide variety of functional requirements including provide electrical power, effectively combat damage, and provide a fuel source. The propulsion system ($DP_1$) and the maneuvering and control system ($DP_2$) also contribute to the ship's ability to conduct extended operations. The rate at which the propulsion system consumes fuel determines the ship's endurance range, thereby affecting the fuel system. The maneuvering and control system assists the ship in detecting and avoiding heavy weather whenever necessary. By avoiding storms and high winds, the ship increases its ability to conduct sustained operations by mitigating potential damage. Proper maneuvering also allows the ship to transit to the desired destination in the most efficient manner, thus avoiding unnecessary fuel consumption. Once again, since this study does not include operating procedures, initially an $O$ replaces the $X$ corresponding to $DP_2$.

Further consideration is required to remove the $X$ signifying the contribution of $DP_6$ to $FR_5$. As stated earlier, the hull causes resistive forces opposing forward movement which must be matched by the propulsion system. The fuel storage system carries the fuel necessary for extended operations. Therefore, the size of the fuel tankage is determined by the fuel required to produce forward motion at a designated speed for a designated range. This motion is opposed by hull resistance. To remove this coupling, the designer must size the fuel storage capacity based on the imposed constraint ($C_{12}$). By adhering to the following constraint, an $O$ replaces the respective $X$.

$$C_{12} = \text{Carry adequate fuel to transit endurance range at endurance speed}$$

$FR_6$, operate on surface of water, is affected by all the stated DPs, $DP_1 - DP_6$. The shape of the hull form, $DP_6$, in large part determines how the ship's weight is supported by the resultant buoyant force. All the DPs comprise the ship's total weight. Due to Archimedes' Principle, the total weight of the ship must equal the weight of the displaced volume of water, so the ship floats and thus operates on the surface of water. Additionally, $DP_4$ contributes to the ship's total resistance characteristics since both the hull and the superstructure contribute to aerodynamic drag.

The rigorous analysis of the interrelationships between the highest level FRs and DPs reveals a decoupled design is in fact achievable. Equation 3.2 is the highest level design equations resulting in the decoupled design. In order to achieve this decoupled design, two additional constraints were placed on the design process and two decisions amending the overall design philosophy (to remove a single coupling) were made. Logical deductions also eliminated three weak FR-DP relationships. Finally, examining the scope of this analysis eliminated five FR-DP relationships caused by operational concerns vice design considerations. The Independence Axiom is satisfied only if the DPs are changed to satisfy the FRs in the proper sequence shown in the lower triangular design matrix.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O \\ x & X & O & O & O & O \\ O & O & X & O & O & O \\ O & O & X & X & O & O \\ X & O & O & O & X & O \\ X & X & X & X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{Bmatrix} \tag{3.2}$$

## 3.3 Constraint Evaluation

For easy reference all design constraints along with associated FRs are listed below. The ensuing discussion outlines the reasoning behind the assigning of constraints to each respective highest level FR. Since the initial constraints bound the design process, it is important to understand their influence prior to commencing the decomposition procedure.

| Constraint | FR |
|---|---|
| $C_1 =$ Initial acquisition cost $\leq \$\ XXM$ (say, $\$\ 750M$) | $FR_1 - FR_6$ |
| $C_2 =$ Average hourly operating cost $\leq \$\ XX$ (say, $\$\ 2{,}600/hr$) | $FR_1 - FR_6$ |
| $C_3 =$ Full load displacement $=$ Total weight | $FR_6$ |
| $C_4 =$ Ensure intact stability (GM $> 0$ ft) | $FR_6$ |
| $C_5 =$ Ensure acceptable transverse dynamic stability ($0.090 \leq GM/B \leq 0.122$) | $FR_6$ |
| $C_6 =$ Installed propulsive power $\geq$ Required propulsive power | $FR_1$ , $FR_6$ |

| | |
|---|---|
| $C_7 =$ Installed electrical power $\geq$ Required electrical power | $FR_5$ |
| $C_8 =$ Total available volume $\geq$ Total required volume | $FR_4$ , $FR_6$ |
| $C_9 =$ Total avail arrangeable area $\geq$ Total req'd arrangeable area | $FR_4$ , $FR_6$ |
| $C_{10} =$ Incorporate design growth margins (weight, KG, propulsion and electrical power) | $FR_1$ , $FR_5$ , $FR_6$ |
| $C_{11} =$ Always operate at the design waterline (DWL) | $FR_6$ |
| $C_{12} =$ Carry adequate fuel to transit endurance range at endurance speed | $FR_1$ , $FR_5$ , $FR_6$ |

$C_1$ and $C_2$ apply to $FR_1 - FR_6$. The fulfillment of each highest level functional requirement by the specified design parameter results in both an initial acquisition and an average hourly operating cost. The initial acquisition cost required to fulfill each FR includes design, research and development, and construction of each necessary DP, as well as difficult to define items such as process overhead. The average hourly operating cost associated with the satisfying of each FR is not necessarily apparent, but does exist due to systems maintenance, preservation, and personnel operating costs.

$C_3$, $C_4$, $C_5$, and $C_{11}$ apply exclusively to $FR_6$ since the method of satisfying this requirement is naturally a hull form. $C_3$ applies solely to the hull form because of the order in which the DPs are set to produce a decoupled design. Since all the DPs defining the total ship weight (except $DP_6$) are determined prior to designing the hull form, it follows that the displaced volume of the hull form must support the weight of all systems. Similar reasoning also dictates that $C_4$ and $C_5$ need only be considered when designing the hull form since the weight of all systems is set before designing the hull. Upon conceiving the hull form, the vertical positioning of all systems are determined. This vertical positioning results in the first factor, the vertical center of gravity, required to calculate GM. The geometry of the hull determines the final value of GM by setting the metacenter.

The coupling between resistance and powering causes $C_{11}$ to be imposed. Therefore, to maintain constant hull resistance, the hull form must operate at a fixed draft. When designing the hull form ($DP_6$) and its associated systems, a means to allow the ship to operate consistently at the DWL must be implemented.

$C_6$ applies to both $FR_1$ and $FR_6$. Since the propulsion system ($DP_1$) is designed to begin the design process, the marine engineer must utilize past experience to set its propulsive capability based on the ship's suspected characteristics. Legacy components with known capabilities comprise the propulsion system (i.e., new engines are not designed). Based on the setting of $DP_1$, the hull form ($DP_6$) must be designed such that $C_5$ is satisfied.

$C_7$ applies solely to $FR_5$. The DP that ensures the ship is capable of conducting sustained underway operations is the support / auxiliary systems ($DP_5$). Within this group of systems is the ship's electrical system. By the time the electrical generation capability of the electrical system must be set, a majority of the systems requiring power input are already set. The marine engineer must once again rely on past experience to project the system's actual required power output such that $C_6$ is satisfied.

$C_8$ and $C_9$ apply to both $FR_4$ and $FR_6$. These two constraints deal with the physical space (volume and area) designed into the shipboard systems and the ship itself. The satisfying of all FRs determines the required space. The satisfying of $FR_6$ with the hull form produces the available space within the hull. But, recall the first design philosophy decision made while deriving the decoupled design equations. By addressing all RCS reduction efforts (a passive means to protect from enemy attack) with the superstructure design, space implications also arise. The designer conceptually designs the superstructure which traditionally houses most combat systems and crew's berthing when satisfying $FR_4$. Therefore, to satisfy both constraints, the space available in both the hull and the superstructure must be evaluated.

$C_{10}$ and $C_{12}$ apply to $FR_1$, $FR_5$, and $FR_6$. Design growth margins are required to allow for systems addition and modification throughout the life cycle of the ship. Since these margins account for potential weight plus required propulsion and electrical power growth, the designer must purposely "over design" the DPs fulfilling $FR_1$, $FR_5$, and $FR_6$ to satisfy $C_{10}$. Expanding on the $C_6$ discussion, the naval architect must utilize past experience to size the fuel tankage considering the selected propulsion engines and the ship's suspected characteristics. Based on the setting of $DP_1$, the fuel storage capability must be sized accordingly, and then the hull form ($DP_6$) must be designed such that $C_{12}$ is satisfied.

## 3.4 Design Decomposition

Functionally decomposing the highest level FRs/DPs and subsequently using the "zigzagging" process to conduct further decomposition defines a warship in hierarchial fashion. As previously stated, decomposition continues until the selected DPs are well understood and designed, i.e. the DPs are legacy systems or components. Appendix B contains the entire warship design comprised of the complete hierarchial fulfillment of the six highest level FRs to their respective leaf nodes and all supporting conceptual design equations. This detailed decomposition facilitates the conducting of functional allocation tradeoff studies when extended one level further at various nodes. Comments pertaining to the FRs, DPs, and coupled design matrix elements as well as additional design process constraints are also contained in Appendix B. All design decisions governing the selection of DPs satisfy the Independence Axiom.

To demonstrate the decomposition process using the described "zigzagging" technique, the total design satisfying $FR_1$, ceasing at one level above each respective tradeoff node, is discussed in detail. A procedure to satisfy $FR_2 - FR_5$ without using extensive decomposition is next discussed. Finally, to demonstrate the utility of the proposed design methodology, the fulfilling of $FR_6$ through rigorous, but not totally complete, decomposition is explained. As with the fulfilling of $FR_2 - FR_5$, this abbreviated decomposition scheme is not totally complete with regards to implementing the functional allocation process[2]. A well defined warship concept exists upon completing the decomposition as outlined.

The design methodology leading to the warship concept demonstrates both a non-iterative approach to ship design, and a rigorous method to assign manning and automation for naval surface combatants. The complete decomposition of $FR_1$ shows the leaf nodes at which functional allocation may occur. The fulfilling of all FRs in the proposed decoupled sequence and culminating in the fulfillment of $FR_6$ likewise shows how to achieve a non-iterative concept design warship. Completing the design process by fulfilling $FR_6$ last defines a procedure to control the resistance and powering coupling. Simply stated, to control this coupling, the designer first designs all required shipboard systems, and then "wraps a hull around the systems."

[2]Detailed decompositions of $FR_2 - FR_6$ facilitating the functional allocation process, along with all corresponding conceptual design equations, are contained in Appendix B. To determine the nodes supporting tradeoffs, where appropriate, an additional level of decomposition is required.

The format for presenting the hierarchial design information starts with listing the parent FR/DP pair followed by the decomposed children FR/DP pairs. Additional design constraints affecting the selection of DPs are also listed. Design equations in conceptual ($X$ and $O$) format are next formulated and discussed for each child level. Finally, the "zigzagging" process is implemented to decompose all resulting branches to the leaf level. Design decisions made at higher levels necessarily influence design decisions at lower levels and consistency must be practiced throughout the decomposition process.

### 3.4.1 Fulfillment of $FR_1$

The decomposition of $FR_1$ and all other highest level FRs plays a large role in achieving the end goal, devising a method to determine the overall impact on the ship design caused by manning and automation tradeoff decisions. Only the complete decomposition of $FR_1$ is presented as a 'proof of concept' demonstrating the use of axiomatic design techniques to outline a rigorous functional allocation procedure. Some leaf nodes presented in the section require an additional level of decomposition to allow manning/automation tradeoffs. For instance, the FR stated as "*Determine pressure*" fulfilled by the DP "*Pressure gage*" leads to a potential tradeoff as follows.

The function of reading the pressure gage may be assigned to either a crewmember, or an automated electronic sensing system. If a crewmember reads it, the pressure is recorded manually. If a sensor reads it, an automated method of recording the pressure must be incorporated into the design. The automated electronic sensing system requires a specified amount of space, electrical power, computing infrastructure, etc. Each crewmember also requires training, space for messing, berthing, protection, environmental control, etc. and contributes to a percentage of the ship's electrical load. Thus, by evaluating the requirements associated with each option, the overall impact on the ship is determined. Chapter 5 contains the extended $FR_1$ decomposition and discusses the functional allocation process.

Recall $FR_1$, $DP_1$, and the applicable design constraints.

$FR_1$ = Move through water $\qquad\qquad$ $DP_1$ = Propulsion system

$C_1 =$ Initial acquisition cost $\leq \$\ XXM$ (say, \$ $750M$)

$C_2 =$ Average hourly operating cost $\leq \$\ XX$ (say, \$ $2,600/hr$)

$C_6 =$ Installed propulsive power $\geq$ Required propulsive power

$C_{10} =$ Incorporate design growth margins (weight, KG, and electrical power)

$C_{12} =$ Carry adequate fuel to transit endurance range at endurance speed

Since the propulsion system is not a leaf node, decomposition proceeds by determining the functions requiring accomplishment by $DP_1$. Appropriate DPs are selected to fulfill these child level FRs. At this level, and all subsequent levels, of decomposition the designer must select cost-effective DPs, in both the acquisition sense and the operational sense, to comply with $C_1$ and $C_2$. The first child level FR/DP pairs follow with the devised decoupled design equations numbered as Equation 3.3.

| | |
|---|---|
| $FR_{1.1}$ = Produce propulsive power to achieve sustained speed | $DP_{1.1}$ = Main propulsion engines |
| $FR_{1.2}$ = Provide propulsive power at usable speed (rpm) | $DP_{1.2}$ = Reduction gear |
| $FR_{1.3}$ = Transfer power to water | $DP_{1.3}$ = CRP propeller |
| $FR_{1.4}$ = Control speed and direction of movement locally | $DP_{1.4}$ = Engineering Operating Station |
| $FR_{1.5}$ = Control speed and direction of movement remotely | $DP_{1.5}$ = Lee helm |

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \\ FR_{1.4} \\ FR_{1.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ X & X & O & O & O \\ O & X & X & O & O \\ X & O & X & X & O \\ X & O & X & X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \\ DP_{1.4} \\ DP_{1.5} \end{Bmatrix} \tag{3.3}$$

$FR_{1.1}$, produce propulsive power to achieve sustained speed, is fulfilled solely by $DP_{1.1}$, main propulsion engines. Two possibilities present themselves, develop new engines or use legacy propulsion engines. If a new engine design is pursued, extensive research, development,

testing, and evaluation (RDT&E) costs must be accepted as contributing to the initial acquisition cost. If legacy engines are selected to comply with the intent of $C_1$, new technologies can be assumed to be developed independently either as military or commercial products, and are only available for selection by the designer when qualified for use. The designer must also consider $C_5$ when selecting $DP_{1.1}$. This is done by roughly predicting the required propulsive power and choosing engines that possess the capability of providing this estimated power. The designed hull form must not produce resistive forces exceeding the available installed power produced by the set engine choice.

For this design, a mechanically driven propulsion system is set by selecting reduction gear ($DP_{1.2}$) to fulfill $FR_{1.2}$, provide propulsive power at usable speed (rpm). The propulsion engines ($DP_{1.1}$) also contribute to the accomplishment of $FR_{1.2}$ because the engine operating speed range affects the required reduction ratio. An additional reason for dependency of $FR_{1.2}$ on $DP_{1.1}$ results because of a design decision allowing the sharing of a common pressurized air source. This design decision is subsequently discussed along with the decomposition.

Propellers transfer power to the water ($FR_{1.3}$). In this case, a controllable reversible pitch (CRP) propeller ($DP_{1.3}$) satisfies this requirement. The amount of power a propeller produces depends on characteristics including number of blades, blade skew, and expanded area ratio. Additionally, the amount of power transferred by the propeller depends on the rotational speed. Rotational speed is determined, and limited by, the reduction gear ($DP_{1.2}$).

The speed and direction of ship movement must be controlled. Following standard Navy design and operational practices, redundant control stations, in the vicinity of the engineering plant (termed local) and not in the vicinity of the engineering plant (termed remote), are required resulting in $FR_{1.4}$ and $FR_{1.5}$. The engineering operating station (EOS) is selected as $DP_{1.4}$ and the lee helm is selected as $DP_{1.5}$. The engineering control center, often called the central control station, houses the EOS allowing control of speed and direction locally. Similarly, the lee helm is positioned on the ship's bridge. The bridge can be thought of as the center where the ship's movement is coordinated and controlled. $DP_{1.1}$ and $DP_{1.3}$ contribute to both FRs because propulsion engines and propellers are actually manipulated to determine the ship's movement. The EOS and the lee helm share a common control air system (as further decomposition shows). Since the lee helm is designed subsequent to the EOS according to the

design equations, $FR_{1.5}$ also relies upon $DP_{1.4}$.

Adhering to the stated format, the branch originating with $DP_{1.1}$, the listed parent DP, is fully decomposed to all respective leaf levels. Five FRs must be accomplished supporting the operation of the main propulsion engines (MPEs). An additional sub-constraint ($C_{12.1}$) limits the selection of $DP_{1.1.2}$. The FR/DP pairs, the constraint, and the design equations given in Equation 3.4 follow.

$FR_{1.1.1}$ = Provide inertia to start engine $DP_{1.1.1}$ = Starting air system

$FR_{1.1.2}$ = Provide fuel for continuous engine operation $DP_{1.1.2}$ = MPE fuel system

$FR_{1.1.3}$ = Cool engine $DP_{1.1.3}$ = MPE lube oil system

$FR_{1.1.4}$ = Provide air to support engine combustion $DP_{1.1.4}$ = Engine inlet ducting

$FR_{1.1.5}$ = Remove combustion products $DP_{1.1.5}$ = Engine exhaust ducting

$C_{12.1}$ = Fuel supply rate must support combined engine specific fuel consumption (sfc)

$$\begin{Bmatrix} FR_{1.1.1} \\ FR_{1.1.2} \\ FR_{1.1.3} \\ FR_{1.1.4} \\ FR_{1.1.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & O & X & O & O \\ O & O & O & X & O \\ O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.1} \\ DP_{1.1.2} \\ DP_{1.1.3} \\ DP_{1.1.4} \\ DP_{1.1.5} \end{Bmatrix} \tag{3.4}$$

The DPs satisfying $FR_{1.1.1} - FR_{1.1.5}$ are functionally independent. Thus, an uncoupled design equation results. $DP_{1.1.1}$, the starting air system, represents the typical pressurized air system. $DP_{1.1.2}$, the MPE fuel system, and $DP_{1.1.3}$, the MPE lube oil system, are fluid systems varying slightly from the typical configuration. Respectively and in the conceptual sense, typical systems fulfill the same functions and therefore may contain identical types of components. For this analysis, all pressurized air systems are comprised of the same component types and all fluid systems are comprised of the same component types unless otherwise noted. The components defining these two types of systems are shown with further decomposition.

$DP_{1.1.4}$, engine inlet ducting, provides a means to supply the engine with the necessary air flow to support combustion ($FR_{1.1.4}$). Once combustion occurs to extract energy from the fuel, $DP_{1.1.5}$, engine exhaust ducting, provides a means for the combustion products to discharge ($FR_{1.1.5}$).

The functions fulfilled by the starting air system ($DP_{1.1.1}$) are defined and the appropriate design parameters are selected producing a decoupled design. The FRs and DPs listed in this decomposition, and the design equations listed in Equation 3.5, are characteristic of the typical pressured air system. For future reference, any system requiring similar functional design is referred to as a *typical pressurized air system.*

| | |
|---|---|
| $FR_{1.1.1.1}$ = Increase air pressure to required pressure | $DP_{1.1.1.1}$ = Air compressor |
| $FR_{1.1.1.2}$ = Hold air at required pressure | $DP_{1.1.1.2}$ = Air flasks |
| $FR_{1.1.1.3}$ = Start / stop air flow | $DP_{1.1.1.3}$ = Valves |
| $FR_{1.1.1.4}$ = Transport air to flask / engine | $DP_{1.1.1.4}$ = Air piping |
| $FR_{1.1.1.5}$ = Determine air pressure | $DP_{1.1.1.5}$ = Pressure gages |

$$\begin{Bmatrix} FR_{1.1.1.1} \\ FR_{1.1.1.2} \\ FR_{1.1.1.3} \\ FR_{1.1.1.4} \\ FR_{1.1.1.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ X & O & X & O & O \\ X & O & X & X & O \\ O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.1.1} \\ DP_{1.1.1.2} \\ DP_{1.1.1.3} \\ DP_{1.1.1.4} \\ DP_{1.1.1.5} \end{Bmatrix} \tag{3.5}$$

An air compressor ($DP_{1.1.1.1}$) increases the ambient air pressure to the pressure required to start the propulsion engines ($FR_{1.1.1.1}$). Once the air reaches this necessary pressure, a means to hold it ($FR_{1.1.1.2}$) must be designed. Air flasks ($DP_{1.1.1.2}$) fulfill this functional requirement. Once the pressurized air is contained within the flasks, it will escape to a lower pressure if given the opportunity as dictated by physics. Therefore, the air pressure (caused by $DP_{1.1.1.1}$) starts the flow of air. But, valves ($DP_{1.1.1.3}$) at designed at specific points in the system to start / stop the air flow ($FR_{1.1.1.3}$) in a controlled manner. These valves are connected to air piping ($DP_{1.1.1.4}$) which actually transport the air from the air compressor to the flask, and from the flask to the engines ($FR_{1.1.1.4}$). Once again, the pressure differential (again, caused by

$DP_{1.1.1.1}$) allows transport to occur. Additionally, the necessary valves ($DP_{1.1.1.3}$) must be properly aligned to transport the air to the desired location. The final function required by the starting air system, determine air pressure ($FR_{1.1.1.5}$), is satisfied exclusively by pressure gages ($DP_{1.1.1.5}$).

All the four digit tiered DPs are leaf nodes, with the exception of $DP_{1.1.1.1}$. The air compressor itself requires a power source. To maintain a decoupled design, the source, the ship's electrical system, is not included in this decomposition. But rather, a method of connecting to this system is designed by decomposition. It is noted that an individual power source for each piece of equipment requiring electrical power could be incorporated into the design. But, by opting not to centralize the power source, it is speculated that both $C_1$ and $C_2$ are disregarded (again due to associated RDT&E costs). Therefore, another conscious design decision is made to follow traditional power generation methodology. The FR/DP pairs defining the final leaf nodes of the $DP_{1.1.1}$ branch are listed with the applicable design equations, Equation 3.6.

$FR_{1.1.1.1.1}$ = Receive electrical power — $DP_{1.1.1.1.1}$ = Electrical hardwire connection point

$FR_{1.1.1.1.2}$ = Energize / de-energize — $DP_{1.1.1.1.2}$ = Control panel

$$\begin{Bmatrix} FR_{1.1.1.1.1} \\ FR_{1.1.1.1.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.1.1.1} \\ DP_{1.1.1.1.2} \end{Bmatrix} \tag{3.6}$$

This electrical power connection decomposition is consistent for numerous shipboard components. Because of this, a standard designation is given to the specified FRs and DPs, along with the accompanying design equations. For future reference, this functional design is referred to as a *typical electrical connection.*

The air compressor, and all other components requiring electrical power, require a point to "plug into" the electrical system. This fact results in $FR_{1.1.1.1.1}$, receive electrical power which is satisfied by $DP_{1.1.1.1.1}$, the electrical hardwire connection point. To ensure continuity of electrical power supply during almost all operational conditions, a hardwiring point is employed rather than an electrical socket. If $DP_{1.1.1.1.1}$ was an electrical socket, power could be lost due to inadvertent disconnect caused by vibration, weapons shock, etc. A method to energize / de-energize the air compressor ($FR_{1.1.1.1.2}$) must also be designed. This FR is fulfilled by

$DP_{1.1.1.1.2}$, a control panel. Without a means of receiving electrical power, the control panel does not function. Therefore, $DP_{1.1.1.1.1}$ also contributes to $FR_{1.1.1.1.2}$.

The functions fulfilled by the MPE fuel system ($DP_{1.1.2}$) are defined and the appropriate design parameters are selected producing a decoupled design. The FRs and DPs listed in this decomposition, and the design equations listed in Equation 3.7 vary slightly from the typical fluid system. The characteristics of the typical fluid system are outlined when discussing the MPE lube oil system.

$FR_{1.1.2.1}$ = Receive fuel from fuel transfer system $\quad DP_{1.1.2.1}$ = Piping connection

$FR_{1.1.2.2}$ = Supply fuel $\quad DP_{1.1.2.2}$ = Engine fuel pump

$FR_{1.1.2.3}$ = Start / stop fuel flow $\quad DP_{1.1.2.3}$ = Valves

$FR_{1.1.2.4}$ = Transport fuel to engine $\quad DP_{1.1.2.4}$ = Engine fuel piping

$FR_{1.1.2.5}$ = Determine fuel pressure $\quad DP_{1.1.2.5}$ = Pressure gages

$$\left\{\begin{array}{c} FR_{1.1.2.1} \\ FR_{1.1.2.2} \\ FR_{1.1.2.3} \\ FR_{1.1.2.4} \\ FR_{1.1.2.5} \end{array}\right\} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & X & X & O & O \\ O & X & X & X & O \\ O & O & O & O & X \end{bmatrix} \left\{\begin{array}{c} DP_{1.1.2.1} \\ DP_{1.1.2.2} \\ DP_{1.1.2.3} \\ DP_{1.1.2.4} \\ DP_{1.1.2.5} \end{array}\right\} \tag{3.7}$$

Since a system to exclusively hold fuel for MPE usage is not designed, the MPE fuel system must receive fuel from the ship's fuel transfer system ($FR_{1.1.2.1}$). The fuel transfer system initially receives fuel from the fuel storage system. This FR is naturally fulfilled by $DP_{1.1.2.1}$, a piping connection. To supply fuel to the engine ($FR_{1.1.2.2}$), an engine fuel pump ($DP_{1.1.2.2}$) is required. As with the starting air system, valves ($DP_{1.1.2.3}$) at designed at specific points in the system to start / stop the fuel flow ($FR_{1.1.2.3}$) in a controlled manner. These valves are connected to fuel piping ($DP_{1.1.2.4}$) which actually transport fuel to the engine ($FR_{1.1.2.4}$). The pressure provided by the fuel pump ($DP_{1.1.2.1}$) starts the flow and also enables transport. The final function required by the MPE fuel system, determine fuel pressure ($FR_{1.1.2.5}$), is satisfied exclusively by pressure gages ($DP_{1.1.2.5}$).

$DP_{1.1.2.2}$ is the only four digit tiered DP remaining that is not a leaf node. The decompo-

sition leading to the leaf level follows with the decoupled design equations given in Equation 3.8.

$FR_{1.1.2.2.1}$ = Activate / de-activate pumps $DP_{1.1.2.2.1}$ = Engine rotation

$FR_{1.1.2.2.2}$ = Control fuel output $DP_{1.1.2.2.2}$ = Engine rotation speed

$$\begin{Bmatrix} FR_{1.1.2.2.1} \\ FR_{1.1.2.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.2.2.1} \\ DP_{1.1.2.2.2} \end{Bmatrix} \tag{3.8}$$

A way to activate / de-activate the fuel pump ($FR_{1.1.2.2.1}$) not requiring external electrical power is utilized by connecting the pump's impeller shaft directly to the engine. Therefore, engine rotation ($DP_{1.1.2.2.1}$) drives the pump fueling the engine. The actual rotation speed ($DP_{1.1.2.2.2}$) controls the fuel output ($FR_{1.1.2.2.2}$). As the engine rotates faster the fuel output increases to support the increased fuel demand. Since rotation speed cannot occur independent of rotation, $DP_{1.1.2.2.1}$ affects $FR_{1.1.2.2.2}$.

The functions fulfilled by the MPE lube oil system ($DP_{1.1.3}$) are defined and the appropriate design parameters are selected producing a decoupled design. The FRs and DPs listed in this decomposition, and the design equations listed in Equation 3.9, are characteristic of the typical fluid system (except, the typical fluid system excludes the last two FR/DP pairs). For future reference, any system requiring similar functional design is referred to as a *typical fluid system.*

$FR_{1.1.3.1}$ = Hold lube oil $DP_{1.1.3.1}$ = MPE lube oil sumps

$FR_{1.1.3.2}$ = Supply / remove lube oil $DP_{1.1.3.2}$ = Pumps

$FR_{1.1.3.3}$ = Start / stop lube oil flow $DP_{1.1.3.3}$ = Valves

$FR_{1.1.3.4}$ = Transport lube oil $DP_{1.1.3.4}$ = MPE lube oil piping

$FR_{1.1.3.5}$ = Determine lube oil quantity $DP_{1.1.3.5}$ = Gages measuring sump level

$FR_{1.1.3.6}$ = Determine lube oil pressure $DP_{1.1.3.6}$ = Pressure gages

$FR_{1.1.3.7}$ = Determine lube oil temperature $DP_{1.1.3.7}$ = Temperature gages

$FR_{1.1.3.8}$ = Cool lube oil $DP_{1.1.3.8}$ = Sea water system

$$\begin{Bmatrix} FR_{1.1.3.1} \\ FR_{1.1.3.2} \\ FR_{1.1.3.3} \\ FR_{1.1.3.4} \\ FR_{1.1.3.5} \\ FR_{1.1.3.6} \\ FR_{1.1.3.7} \\ FR_{1.1.3.8} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O & O & O \\ O & X & O & O & O & O & O & O \\ O & X & X & O & O & O & O & O \\ O & X & X & X & O & O & O & O \\ O & O & O & O & X & O & O & O \\ O & O & O & O & O & X & O & O \\ O & O & O & O & O & O & X & O \\ O & O & O & O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.3.1} \\ DP_{1.1.3.2} \\ DP_{1.1.3.3} \\ DP_{1.1.3.4} \\ DP_{1.1.3.5} \\ DP_{1.1.3.6} \\ DP_{1.1.3.7} \\ DP_{1.1.3.8} \end{Bmatrix} \tag{3.9}$$

Unlike the MPE fuel system, the MPE lube oil system is self-contained causing the need for a means to hold the lube oil ($FR_{1.1.3.1}$). The MPE lube oil sumps ($DP_{1.1.3.1}$) fulfill this requirement. The logic pertaining to the satisfying of $FR_{1.1.3.2} - FR_{1.1.3.4}$ parallels that of $FR_{1.1.2.2} - FR_{1.1.2.4}$. Since, engine cooling is vital to continuous engine operation, several parameters require monitoring. Specifically, lube oil quantity ($FR_{1.1.3.5}$), pressure ($FR_{1.1.3.6}$), and temperature ($FR_{1.1.3.7}$) must be determined on a continual basis. These functions are fulfilled by $DP_{1.1.3.5}$, $DP_{1.1.3.6}$ , and $DP_{1.1.3.7}$ respectively. A method to dissipate the engine heat extracted by the lube oil is also necessary for continuous engine operation. The sea water cooling system ($DP_{1.1.3.8}$) does this by acting as a heat exchanger to cool the lube oil ($FR_{1.1.3.8}$).

$DP_{1.1.3.2}$ is decomposed exactly like $DP_{1.1.2.2}$. Therefore, the FR/DP pairs and design equation (Equation 3.10) are given without further explanation.

$FR_{1.1.3.2.1}$ = Activate / de-activate pumps $\quad DP_{1.1.3.2.1}$ = Engine rotation

$FR_{1.1.3.2.2}$ = Control lube oil output $\quad DP_{1.1.3.2.2}$ = Engine rotation speed

$$\begin{Bmatrix} FR_{1.1.3.2.1} \\ FR_{1.1.3.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.3.2.1} \\ DP_{1.1.3.2.2} \end{Bmatrix} \tag{3.10}$$

The sea water system ($DP_{1.1.3.8}$) is a modified fluid system because it is not self-contained, and does not require comprehensive monitoring. The decomposition of $DP_{1.1.3.8}$ copies that of $DP_{1.1.2}$. Because of this, no further discussion follows and only the FR/DP pairs and the

decoupled design equation (Equation 3.11) are given.

$FR_{1.1.3.8.1}$ = Receive / discharge cooling water from / to sea — $DP_{1.1.3.8.1}$ = Hull openings

$FR_{1.1.3.8.2}$ = Supply / remove sea water — $DP_{1.1.3.8.2}$ = Pumps

$FR_{1.1.3.8.3}$ = Start / stop sea water flow — $DP_{1.1.3.8.3}$ = Valves

$FR_{1.1.3.8.4}$ = Transport sea water — $DP_{1.1.3.8.4}$ = Sea water piping

$FR_{1.1.3.8.5}$ = Determine sea water pressure — $DP_{1.1.3.8.5}$ = Pressure gages

$$\left\{\begin{array}{c} FR_{1.1.3.8.1} \\ FR_{1.1.3.8.2} \\ FR_{1.1.3.8.3} \\ FR_{1.1.3.8.4} \\ FR_{1.1.3.8.5} \end{array}\right\} = \left[\begin{array}{ccccc} X & O & O & O & O \\ O & X & O & O & O \\ O & X & X & O & O \\ O & X & X & X & O \\ O & O & O & O & X \end{array}\right] \left\{\begin{array}{c} DP_{1.1.3.8.1} \\ DP_{1.1.3.8.2} \\ DP_{1.1.3.8.3} \\ DP_{1.1.3.8.4} \\ DP_{1.1.3.8.5} \end{array}\right\} \tag{3.11}$$

The pumps used to supply sea water cooling ($DP_{1.1.3.8.2}$) require electrical power. As stated earlier, the typical electrical connection decomposition fulfills these associated functions. For decomposition numbering continuity, the standard FR/DP pairs and design equations (Equation 3.12) are listed.

$FR_{1.1.3.8.2.1}$ = Receive electrical power — $DP_{1.1.3.8.2.1}$ = Electrical hardwire connection point

$FR_{1.1.3.8.2.2}$ = Energize / de-energize — $DP_{1.1.3.8.2.2}$ = Control panel

$$\left\{\begin{array}{c} FR_{1.1.3.8.2.1} \\ FR_{1.1.3.8.2.2} \end{array}\right\} = \left[\begin{array}{cc} X & O \\ X & X \end{array}\right] \left\{\begin{array}{c} DP_{1.1.3.8.2.1} \\ DP_{1.1.3.8.2.2} \end{array}\right\} \tag{3.12}$$

Next, $DP_{1.2}$, the reduction gear, is fully decomposed to all respective leaf levels. Two FRs result from selecting reduction gear to fulfill $FR_{1.2}$, provide propulsive power at usable speed (rpm). These two FRs start sub-branches which grow to reach leaf levels. The FR/DP pairs and the uncoupled design equations given in Equation 3.13 follow.

$FR_{1.2.1}$ = Connect to engine $\quad$ $DP_{1.2.1}$ = Clutch

$FR_{1.2.2}$ = Cool reduction gear $\quad$ $DP_{1.2.2}$ = Lube oil system

$$\begin{Bmatrix} FR_{1.2.1} \\ FR_{1.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP_{1.2.1} \\ DP_{1.2.2} \end{Bmatrix} \tag{3.13}$$

A reduction gear alone cannot provide propulsive power. The main propulsion engines fulfill this function, $FR_{1.1}$. Therefore, a means to transfer the power via connection to the MPE ($FR_{1.2.1}$) is required. A clutch ($DP_{1.2.1}$) is selected to satisfy this requirement. When the reduction gear turns, friction results from the rubbing of the meshed gears. When friction exists, so does heat. A method of lubricating the interface, which therefore cools the reduction gear ($FR_{1.2.2}$), must be included in the design. The lube oil system ($DP_{1.2.2}$) meets this need. Both these children require further decomposition.

Selection of a clutch to fulfill $FR_{1.2.1}$ leads to additional decomposition. Two FRs result and the necessary DPs are selected to produce the decoupled design shown in Equation 3.14.

$FR_{1.2.1.1}$ = Activate / de-activate clutch $\quad$ $DP_{1.2.1.1}$ = Clutch air system

$FR_{1.2.1.2}$ = Engage engine shaft $\quad$ $DP_{1.2.1.2}$ = Rubber boot

$$\begin{Bmatrix} FR_{1.2.1.1} \\ FR_{1.2.1.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.2.1.1} \\ DP_{1.2.1.2} \end{Bmatrix} \tag{3.14}$$

Air pressure activates the clutch and the lack of air pressure de-activates it ($FR_{1.2.1.1}$). The clutch air system ($DP_{1.2.1.1}$) produces the air pressure fulfilling the function. To engage the clutch to the engine shaft ($FR_{1.2.1.2}$), a rubber boot ($DP_{1.2.1.2}$) inflates from air provided by the clutch air system ($DP_{1.2.1.1}$). Thus, the fulfilling of $FR_{1.2.1.2}$ also relies upon $DP_{1.2.1.1}$. $DP_{1.2.1.2}$ is a leaf node.

The decomposition of $DP_{1.2.1.1}$ is similar to that of $DP_{1.1.1}$, the starting air system. In fact, it follows the decomposition of this typical air system with only a slight difference. As mentioned earlier, this system is not stand-alone. It receives air from the MPE starting air system ($FR_{1.2.1.1.1}$) through means of a piping connection ($DP_{1.2.1.1.1}$). The decision to allow the system dependency results because the starting of MPEs and activating of the clutch never

occur simultaneously. MPEs must be started and then the clutch is activated to engage the reduction gear. Therefore, failure of either system due to insufficient air is not anticipated. All decomposed FR/DP pairs are listed below along with the decoupled design equations, Equation 3.15. No additional discussion is included about this modified typical pressurized air system.

$FR_{1.2.1.1.1}$ = Receive air from MPE starting air system — $DP_{1.2.1.1.1}$ = Piping connection

$FR_{1.2.1.1.2}$ = Start / stop air flow — $DP_{1.2.1.1.2}$ = Valves

$FR_{1.2.1.1.3}$ = Transport air to flask / engine — $DP_{1.2.1.1.3}$ = Air piping

$FR_{1.2.1.1.4}$ = Determine air pressure — $DP_{1.2.1.1.4}$ = Pressure gages

$$\begin{Bmatrix} FR_{1.2.1.1.1} \\ FR_{1.2.1.1.2} \\ FR_{1.2.1.1.3} \\ FR_{1.2.1.1.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ X & X & O & O \\ X & X & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{1.2.1.1.1} \\ DP_{1.2.1.1.2} \\ DP_{1.2.1.1.3} \\ DP_{1.2.1.1.4} \end{Bmatrix} \tag{3.15}$$

The decomposition of $DP_{1.2.2}$ also parallels that of $DP_{1.1.3}$, the MPE lube oil system. The lube oil system supporting the reduction gear decomposes identically to the typical fluid system except it requires two additional FRs. Because clearances between the meshed teeth are critical, the presence of surface corrosion and/or particulates can potentially make the reduction gear inoperational. To ensure lubrication is available even when the reduction gear is not turning ($FR_{1.2.2.2}$), electrically powered lube oil standby pumps ($DP_{1.2.2.2}$) supply / remove lube oil in this contingency. To ensure the lube oil is free of sediment ($FR_{1.2.2.10}$), a purifier ($DP_{1.2.2.10}$) is designed into the system. All decomposed FR/DP pairs are listed below along with the decoupled design equation, Equation 3.16. Additional discussion pertaining to the decomposition of this modified typical fluid system does not follow.

$FR_{1.2.2.1}$ = Hold lube oil — $DP_{1.2.2.1}$ = Lube oil sumps

$FR_{1.2.2.2}$ = Supply / remove lube oil (reduction gear not turning) — $DP_{1.2.2.2}$ = Lube oil standby pumps

$FR_{1.2.2.3}$ = Supply / remove lube oil (reduction gear turning) — $DP_{1.2.2.3}$ = Pumps

$FR_{1.2.2.4}$ = Start / stop lube oil flow — $DP_{1.2.2.4}$ = Valves

$FR_{1.2.2.5}$ = Transport lube oil — $DP_{1.2.2.5}$ = Lube oil piping

$FR_{1.2.2.6}$ = Determine lube oil quantity — $DP_{1.2.2.6}$ = Gages measuring sump level

$FR_{1.2.2.7}$ = Determine lube oil pressure — $DP_{1.2.2.7}$ = Pressure gages

$FR_{1.2.2.8}$ = Determine lube oil temperature — $DP_{1.2.2.8}$ = Temperature gages

$FR_{1.2.2.9}$ = Cool lube oil — $DP_{1.2.2.9}$ = Sea water system

$FR_{1.2.2.10}$ = Ensure lube oil free of sediment — $DP_{1.2.2.10}$ = Purifier

$$\left\{\begin{array}{c} FR_{1.2.2.1} \\ FR_{1.2.2.2} \\ FR_{1.2.2.3} \\ FR_{1.2.2.4} \\ FR_{1.2.2.5} \\ FR_{1.2.2.6} \\ FR_{1.2.2.7} \\ FR_{1.2.2.8} \\ FR_{1.2.2.9} \\ FR_{1.2.2.10} \end{array}\right\} = \left[\begin{array}{cccccccccc} X & O & O & O & O & O & O & O & O & O \\ O & X & O & O & O & O & O & O & O & O \\ O & O & X & O & O & O & O & O & O & O \\ O & X & X & X & O & O & O & O & O & O \\ O & X & X & X & X & O & O & O & O & O \\ O & O & O & O & O & X & O & O & O & O \\ O & O & O & O & O & O & X & O & O & O \\ O & O & O & O & O & O & O & X & O & O \\ O & O & O & O & O & O & O & O & X & O \\ O & O & O & O & O & O & O & O & O & X \end{array}\right] \left\{\begin{array}{c} DP_{1.2.2.1} \\ DP_{1.2.2.2} \\ DP_{1.2.2.3} \\ DP_{1.2.2.4} \\ DP_{1.2.2.5} \\ DP_{1.2.2.6} \\ DP_{1.2.2.7} \\ DP_{1.2.2.8} \\ DP_{1.2.2.9} \\ DP_{1.2.2.10} \end{array}\right\} \quad (3.16)$$

The lube oil standby pumps are electrically powered. Therefore, the typical electrical connection is needed. $DP_{1.2.2.2}$ follows this standard decomposition, FR/DP pairs, and design equations (Equation 3.17) are given without further explanation.

$FR_{1.2.2.2.1}$ = Receive electrical power — $DP_{1.2.2.2.1}$ = Electrical hardwire connection point

$FR_{1.2.2.2.2}$ = Energize / de-energize — $DP_{1.2.2.2.2}$ = Control panel

$$\left\{ \begin{array}{c} FR_{1.2.2.2.1} \\ FR_{1.2.2.2.2} \end{array} \right\} = \left[ \begin{array}{cc} X & O \\ X & X \end{array} \right] \left\{ \begin{array}{c} DP_{1.2.2.2.1} \\ DP_{1.2.2.2.2} \end{array} \right\} \tag{3.17}$$

The pumps supplying lube oil to the reduction gear when it is turning ($DP_{1.2.2.3}$) are driven by a rotating shaft just as the pumps supplying lube oil to the MPEs. Thus, the decomposition of $DP_{1.2.2.3}$ parallels the decomposition of $DP_{1.1.3.2}$. The FR/DP pairs are listed for completeness and Equation 3.18 is the design equations.

$FR_{1.2.2.3.1}$ = Activate / de-activate pumps $DP_{1.2.2.3.1}$ = Reduction gear rotation

$FR_{1.2.2.3.2}$ = Control lube oil output $DP_{1.2.2.3.2}$ = Reduction gear rotation speed

$$\left\{ \begin{array}{c} FR_{1.2.2.3.1} \\ FR_{1.2.2.3.2} \end{array} \right\} = \left[ \begin{array}{cc} X & O \\ X & X \end{array} \right] \left\{ \begin{array}{c} DP_{1.2.2.3.1} \\ DP_{1.2.2.3.2} \end{array} \right\} \tag{3.18}$$

Since $DP_{1.2.2.9}$ fulfills the exact same function as $DP_{1.1.3.8.1}$, the same decomposition is followed. The same DPs define the same type of system supporting a different piece of equipment. All FR/DP sets are listed, as are the two sets of design equations (Equations 3.19 and 3.20) growing to the leaf level. Additional discussion is neither undertaken, nor required.

$FR_{1.2.2.9.1}$ = Receive / discharge cooling water from / to sea $DP_{1.2.2.9.1}$ = Hull openings

$FR_{1.2.2.9.2}$ = Supply / remove sea water $DP_{1.2.2.9.2}$ = Pumps

$FR_{1.2.2.9.3}$ = Start / stop sea water flow $DP_{1.2.2.9.3}$ = Valves

$FR_{1.2.2.9.4}$ = Transport sea water $DP_{1.2.2.9.4}$ = Sea water piping

$FR_{1.2.2.9.5}$ = Determine sea water pressure $DP_{1.2.2.9.5}$ = Pressure gages

$$\begin{Bmatrix} FR_{1.2.2.9.1} \\ FR_{1.2.2.9.2} \\ FR_{1.2.2.9.3} \\ FR_{1.2.2.9.4} \\ FR_{1.2.2.9.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & X & X & O & O \\ O & X & X & X & O \\ O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{1.2.2.9.1} \\ DP_{1.2.2.9.2} \\ DP_{1.2.2.9.3} \\ DP_{1.2.2.9.4} \\ DP_{1.2.2.9.5} \end{Bmatrix} \tag{3.19}$$

$FR_{1.2.2.9.2.1}$ = Receive electrical power $DP_{1.2.2.9.2.1}$ = Electrical hardwire connection point

$FR_{1.2.2.9.2.2}$ = Energize / de-energize $DP_{1.2.2.9.2.2}$ = Control panel

$$\begin{Bmatrix} FR_{1.2.2.9.2.1} \\ FR_{1.2.2.9.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.2.2.9.2.1} \\ DP_{1.2.2.9.2.2} \end{Bmatrix} \tag{3.20}$$

The final leaf node in the $DP_{1.2}$ sub-branch appears after decomposing $DP_{1.2.2.10}$, the purifier. Like many shipboard machines, the purifier requires electrical power to operate. Therefore, without further explanation, the typical electrical connection decomposition is used. The design equations in Equation 3.21 and the FR/DP pairs are again listed for continuity.

$FR_{1.2.2.10.1}$ = Receive electrical power $DP_{1.2.2.10.1}$ = Electrical hardwire connection point

$FR_{1.2.2.10.2}$ = Energize / de-energize $DP_{1.2.2.10.2}$ = Control panel

$$\begin{Bmatrix} FR_{1.2.2.10.1} \\ FR_{1.2.2.10.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.2.2.10.1} \\ DP_{1.2.2.10.2} \end{Bmatrix} \tag{3.21}$$

With another sub-branch fully defined, focus shifts to fully decomposing $DP_{1.3}$, the CRP propeller, to all respective leaf levels. Three FRs result from selecting this DP to satisfy $FR_{1.3}$. These FRs and respective DPs are listed. Also, the resulting decoupled design equations are stated in Equation 3.22.

$FR_{1.3.1}$ = Receive speed input (rpm's) from reduction gear — $DP_{1.3.1}$ = Shaft

$FR_{1.3.2}$ = Control thrust direction (fore / aft) — $DP_{1.3.2}$ = Blade pitch angle

$FR_{1.3.3}$ = Produce thrust — $DP_{1.3.3}$ = Propeller blades

$$\begin{Bmatrix} FR_{1.3.1} \\ FR_{1.3.2} \\ FR_{1.3.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & X & X \end{bmatrix} \begin{Bmatrix} DP_{1.3.1} \\ DP_{1.3.2} \\ DP_{1.3.3} \end{Bmatrix} \tag{3.22}$$

The propeller turns at the rate of the reduction gear. In order to receive the speed input ($FR_{1.3.1}$), the propeller is connected to the reduction gear via a shaft ($DP_{1.3.1}$). To control the thrust direction ($FR_{1.3.2}$) of a CRP propeller, the blade pitch angle ($DP_{1.3.2}$) is shifted. If a fixed pitch propeller were used to satisfy $FR_{1.3}$, the direction of propeller rotation is reversed to change the thrust direction from fore to aft. Two factors influence the production of thrust ($FR_{1.3.3}$) by a CRP propeller operating at constant rotational speed. These factors are varying the blade pitch angle ($DP_{1.3.2}$) and the propeller blade characteristics ($DP_{1.3.3}$). These blade characteristics naturally are the same factors which determine the amount power transferred to the water, number of blades, expanded area ratio, etc.

$DP_{1.3.1}$ and $DP_{1.3.3}$ are at the leaf level, but $DP_{1.3.2}$ requires further decomposition. The following two FRs, fulfilled by the corresponding DPs, support the blade pitch angle. Equation 3.23 is the respective design equations.

$FR_{1.3.2.1}$ = Allow pitch angle variation — $DP_{1.3.2.1}$ = Pivotal blade connection at hub

$FR_{1.3.2.2}$ = Control pitch angle — $DP_{1.3.2.2}$ = CPP hydraulic system

$$\begin{Bmatrix} FR_{1.3.2.1} \\ FR_{1.3.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ x & X \end{bmatrix} \begin{Bmatrix} DP_{1.3.2.1} \\ DP_{1.3.2.2} \end{Bmatrix} \tag{3.23}$$

Pivotal blade connections at the hub ($DP_{1.3.2.1}$) are the feature of a CRP propeller allowing pitch angle variation ($FR_{1.3.2.1}$). These connections limit pitch angle rotation, i.e. the blade

cannot rotate 360°. Thus, control of the pitch angle ($FR_{1.3.2.2}$) is accomplished by the controllable pitch propeller (CPP) hydraulic system ($DP_{1.3.2.2}$). The CPP hydraulic system controls the pitch of the CRP propeller. Because $DP_{1.2.3.1}$ limits the rotation, it sets the forward and reverse pitch angle bounds; thereby weakly affecting pitch angle control ($FR_{1.3.2.1}$).

The CPP hydraulic system ($DP_{1.3.2.2}$) decomposes similar to typical fluid system except it has one additional functional requirement. Since the propeller blade rotates in opposite directions to produce fore and aft thrust, a method of directing the flow to achieve the desired blade rotation ($FR_{1.3.2.2.4}$) must be designed. Solenoid valves ($DP_{1.3.2.2.4}$) satisfy this additional FR. Hydraulic oil must be supplied (by $DP_{1.3.2.2.2}$) and the necessary valves ($DP_{1.3.2.2.3}$) must be properly aligned in order to direct flow. All germane FR/DP pairs are listed below and the modified typical fluid system design equations are given in Equation 3.24.

| | |
|---|---|
| $FR_{1.3.2.2.1}$ = Hold hydraulic oil | $DP_{1.3.2.2.1}$ = Hydraulic oil sumps |
| $FR_{1.3.2.2.2}$ = Supply / return hydraulic oil | $DP_{1.3.2.2.2}$ = Pumps |
| $FR_{1.3.2.2.3}$ = Start / stop hydraulic oil flow | $DP_{1.3.2.2.3}$ = Valves |
| $FR_{1.3.2.2.4}$ = Direct hydraulic oil flow | $DP_{1.3.2.2.4}$ = Solenoid valves |
| $FR_{1.3.2.2.5}$ = Transport hydraulic oil to propeller / sump | $DP_{1.3.2.2.5}$ = Hydraulic oil piping |
| $FR_{1.3.2.2.6}$ = Determine hydraulic oil quantity | $DP_{1.3.2.2.6}$ = Gages measuring sump level |
| $FR_{1.3.2.2.7}$ = Determine hydraulic oil pressure | $DP_{1.3.2.2.7}$ = Pressure gages |

$$\begin{Bmatrix} FR_{1.3.2.2.1} \\ FR_{1.3.2.2.2} \\ FR_{1.3.2.2.3} \\ FR_{1.3.2.2.4} \\ FR_{1.3.2.2.5} \\ FR_{1.3.2.2.6} \\ FR_{1.3.2.2.7} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O & O \\ O & X & O & O & O & O & O \\ O & X & X & O & O & O & O \\ O & X & X & X & O & O & O \\ O & X & X & O & X & O & O \\ O & O & O & O & O & X & O \\ O & O & O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{1.3.2.2.1} \\ DP_{1.3.2.2.2} \\ DP_{1.3.2.2.3} \\ DP_{1.3.2.2.4} \\ DP_{1.3.2.2.5} \\ DP_{1.3.2.2.6} \\ DP_{1.3.2.2.7} \end{Bmatrix} \tag{3.24}$$

Two of the CPP hydraulic oil system components require electrical power. The pumps ($DP_{1.3.2.2.2}$) and the solenoid valves ($DP_{1.3.2.2.4}$) decompose one more level using the typical electrical connection methodology. All necessary FR/DP sets and design equations (Equations 3.25 and 3.26) are listed below without further discussion.

$FR_{1.3.2.2.2.1}$ = Receive electrical power — $DP_{1.3.2.2.2.1}$ = Electrical hardwire connection point

$FR_{1.3.2.2.2.2}$ = Energize / de-energize — $DP_{1.3.2.2.2.2}$ = Control panel

$$\begin{Bmatrix} FR_{1.3.2.2.2.1} \\ FR_{1.3.2.2.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.3.2.2.2.1} \\ DP_{1.3.2.2.2.2} \end{Bmatrix} \tag{3.25}$$

$FR_{1.3.2.2.4.1}$ = Receive electrical power — $DP_{1.3.2.2.4.1}$ = Electrical hardwire connection point

$FR_{1.3.2.2.4.2}$ = Energize / de-energize — $DP_{1.3.2.2.4.2}$ = Control panel

$$\begin{Bmatrix} FR_{1.3.2.2.4.1} \\ FR_{1.3.2.2.4.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.3.2.2.4.1} \\ DP_{1.3.2.2.4.2} \end{Bmatrix} \tag{3.26}$$

Decomposition of the final two $FR_1$ sub-branches progresses similarly. Therefore, the decomposition of the parent design parameters, $DP_{1.4}$ (the engineering operation station) and $DP_{1.5}$ (the lee helm), is accomplished in tandem. Both FR/DP sets and design equations (Equations 3.27 and 3.28) are listed below. At each level, the portion pertaining to the $FR_{1.4}$ sub-branch is listed first followed by the portion pertaining to the $FR_{1.5}$ sub-branch.

$FR_{1.4.1}$ = Input desired speed and direction of movement — $DP_{1.4.1}$ = Throttle control

$FR_{1.4.2}$ = Display input — $DP_{1.4.2}$ = Indicator gage

$FR_{1.4.3}$ = Produce desired engine speed / propeller pitch combination — $DP_{1.4.3}$ = Propulsion control air system

$$\begin{Bmatrix} FR_{1.4.1} \\ FR_{1.4.2} \\ FR_{1.4.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ x & O & X \end{bmatrix} \begin{Bmatrix} DP_{1.4.1} \\ DP_{1.4.2} \\ DP_{1.4.3} \end{Bmatrix} \tag{3.27}$$

$FR_{1.5.1}$ = Input desired speed and direction of movement

$DP_{1.5.1}$ = Throttle control

$FR_{1.5.2}$ = Display input

$DP_{1.5.2}$ = Indicator gage

$FR_{1.5.3}$ = Produce desired engine speed / propeller pitch combination

$DP_{1.5.3}$ = Propulsion control air system

$$\begin{Bmatrix} FR_{1.5.1} \\ FR_{1.5.2} \\ FR_{1.5.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ x & O & X \end{bmatrix} \begin{Bmatrix} DP_{1.5.1} \\ DP_{1.5.2} \\ DP_{1.5.3} \end{Bmatrix} \tag{3.28}$$

As mentioned earlier, the ship's speed and direction of movement are controlled at local and remote locations (with respect to proximity with the engineering plant). At each of these locations, the design needs a way to input the desired speed and direction of movement ($FR_{1.4.1}$ and $FR_{1.5.1}$). The means to accomplish both FRs is a throttle control, one on the EOS ($DP_{1.4.1}$) and one on the lee helm ($DP_{1.5.1}$). An indicator gage ($DP_{1.4.2}$ and $DP_{1.5.2}$) displays this input ($FR_{1.4.2}$ and $FR_{1.5.2}$). The input activates the propulsion control air system ($DP_{1.4.3}$ and $DP_{1.5.3}$) to produce the necessary engine speed and propeller pitch combination ($FR_{1.4.3}$ and $FR_{1.5.3}$). Because activation of the propulsion control air system is dependent on the throttle control , the desired propulsion combination may not actually be achieved due to possible calibration inconsistencies. Therefore $DP_{1.4.1}$ and $DP_{1.5.1}$ affect $FR_{1.4.3}$ and $FR_{1.5.3}$.

This design incorporates an exclusive propulsion control air system that is operated from either the local or remote stations. This decision resulted because both stations require the air at the same pressure to functionally operate. The propulsion starting air and clutch air systems require air at higher pressures. Therefore, by designing the propulsion control air system independently, the need for reducing stations is eliminated. Since the system controls

the engine speed and propeller pitch from both locations, a designated valve ($DP_{1.4.3.6}$) transfers control between both locations ($FR_{1.4.3.6}$). Aside from this addition, this system decomposes as a typical pressurized air system and requires a typical electrical connection. This decomposition and the all design equations (Equations 3.29 and 3.30) are shown below.

$FR_{1.4.3.1}$ = Increase air pressure to required pressure — $DP_{1.4.3.1}$ = Air compressor

$FR_{1.4.3.2}$ = Hold air at required pressure — $DP_{1.4.3.2}$ = Air flasks

$FR_{1.4.3.3}$ = Start / stop air flow — $DP_{1.4.3.3}$ = Valves

$FR_{1.4.3.4}$ = Transport air to flask / engine — $DP_{1.4.3.4}$ = Air piping

$FR_{1.4.3.5}$ = Determine air pressure — $DP_{1.4.3.5}$ = Pressure gages

$FR_{1.4.3.6}$ = Transfer control between local / remote stations — $DP_{1.4.3.6}$ = Transfer valve

$$\begin{Bmatrix} FR_{1.4.3.1} \\ FR_{1.4.3.2} \\ FR_{1.4.3.3} \\ FR_{1.4.3.4} \\ FR_{1.4.3.5} \\ FR_{1.4.3.6} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O \\ O & X & O & O & O & O \\ X & O & X & O & O & O \\ X & O & X & X & O & O \\ O & O & O & O & X & O \\ O & O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{1.4.3.1} \\ DP_{1.4.3.2} \\ DP_{1.4.3.3} \\ DP_{1.4.3.4} \\ DP_{1.4.3.5} \\ DP_{1.4.3.6} \end{Bmatrix} \tag{3.29}$$

$FR_{1.4.3.1.1}$ = Receive electrical power — $DP_{1.4.3.1.1}$ = Electrical hardwire connection point

$FR_{1.4.3.1.2}$ = Energize / de-energize — $DP_{1.4.3.1.2}$ = Control panel

$$\begin{Bmatrix} FR_{1.4.3.1.1} \\ FR_{1.4.3.1.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.4.3.1.1} \\ DP_{1.4.3.1.2} \end{Bmatrix} \tag{3.30}$$

The decomposition of the $FR_1$ sub-branch is complete and all five sub-branches are now defined with detailed decomposition. Therefore, the first branch of the design originating with $FR_1$, move through water, and progressing to all respective leaf levels is complete. Conceptual design equations are formulated such that the entire decomposition satisfies the Independence

Axiom.

### 3.4.2 Fulfillment of $FR_2$, $FR_3$, $FR_4$, and $FR_5$

$FR_2$, $FR_3$, $FR_4$, and $FR_5$ are decomposed only in very coarse detail. Decomposition stops once the major systems or components fulfilling each FR are defined. The goal is to define these necessary parameters at high levels, thus abbreviating the design hierarchy. Traditionally, many of the items satisfying $FR_2 - FR_5$ are legacy systems or components. Thus, the naval architect often either accesses a database containing each item's weight, area, volume, and electrical power requirement, or uses parametric relationships to identify each of these system parameters. For concept level design, these values suffice and therefore account for the placement of this equipment on the ship. As stated above, Appendix B contains detailed decomposition of all FRs to support the functional allocation process. $C_1$ and $C_2$ pertain to $FR_2 - FR_5$. Additional constraints for each branch are listed and discussed when appropriate.

Continuing the decomposition procedure, $FR_2$ and $DP_2$ are listed. The child level FR/DP pairs also follow with the decoupled design equations numbered as Equation 3.31.

$FR_2$ = Maintain desired course — $DP_2$ = Maneuvering and control system

$FR_{2.1}$ = Determine if course is "safe" — $DP_{2.1}$ = Navigation equipment

$FR_{2.2}$ = Alter existing course — $DP_{2.2}$ = Rudder

$FR_{2.3}$ = Maneuver alongside pier — $DP_{2.3}$ = Bow thrusters / APU's

$$\begin{Bmatrix} FR_{2.1} \\ FR_{2.2} \\ FR_{2.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & X & X \end{bmatrix} \begin{Bmatrix} DP_{2.1} \\ DP_{2.2} \\ DP_{2.3} \end{Bmatrix} \tag{3.31}$$

$FR_{2.1}$, determine if existing course is "safe," refers to ensuring that the desired course is unobstructed. Obstructions are either on the water's surface, such as land and other surface vessels, or underneath the water's surface, primarily the ocean floor not being sufficiently deep for the ship's operating draft. The method for physically identifying obstructions and predicting unsafe operating areas (done by determining the ship's position and comparing it to a chart

defining the position characteristics) is navigation equipment ($DP_{2.1}$). Implementing standard navigation equipment into the design allows decomposition of the $FR_{2.1}$ sub-branch to cease. The rudder ($DP_{2.2}$) alters the ship's course ($FR_{2.2}$). The rudder is external to the ship hull, but its support systems are enclosed within the hull. Therefore, to account for these systems, further decomposition continues. $DP_{2.2}$ also contributes to $FR_{2.3}$, maneuver alongside the pier. The primary means of satisfying this requirement is $DP_{2.3}$, bow thrusters / auxiliary propulsion units (APU's). Following the same logic associated with the rudder, $DP_{2.3}$ also requires additional decomposition.

Decomposition of $DP_{2.2}$ and $DP_{2.3}$ progress similarly. Thus, the decompositions are conducted in a parallel fashion and differences are noted as they arise. Both lower level sets of FR/DP pairs along with the design equations (Equations 3.32 and 3.33) are given next.

| | |
|---|---|
| $FR_{2.2.1}$ = Control rudder movement locally | $DP_{2.2.1}$ = After steering gear |
| $FR_{2.2.2}$ = Control rudder movement remotely | $DP_{2.2.2}$ = Helm |

$$\begin{Bmatrix} FR_{2.2.1} \\ FR_{2.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{2.2.1} \\ DP_{2.2.2} \end{Bmatrix} \tag{3.32}$$

| | |
|---|---|
| $FR_{2.3.1}$ = Ensure maneuverability to port / starboard | $DP_{2.3.1}$ = Pivotal (360 degrees) mount |
| $FR_{2.3.2}$ = Control thruster direction / thrust locally | $DP_{2.3.2}$ = Thruster local control station |
| $FR_{2.3.3}$ = Control thruster direction / thrust remotely | $DP_{2.3.3}$ = Thruster control station |
| $FR_{2.3.4}$ = Receive electrical power | $DP_{2.3.4}$ = Electrical hardwire connection point |
| $FR_{2.3.5}$ = Energize / de-energize | $DP_{2.3.5}$ = Control panel |

$$\begin{Bmatrix} FR_{2.3.1} \\ FR_{2.3.2} \\ FR_{2.3.3} \\ FR_{2.4.4} \\ FR_{2.3.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & X & X & O & O \\ O & O & O & X & O \\ O & O & O & X & X \end{bmatrix} \begin{Bmatrix} DP_{2.3.1} \\ DP_{2.3.2} \\ DP_{2.3.3} \\ DP_{2.3.4} \\ DP_{2.3.5} \end{Bmatrix} \tag{3.33}$$

Both the rudder and the bow thruster must be controlled locally ($FR_{2.2.1}$ and $FR_{2.3.2}$, respectively) and remotely ($FR_{2.2.2}$ and $FR_{2.3.3}$, respectively). Because maintaining control of ship's movement is imperative, especially when in close proximity to the pier, U.S. Navy designs mandate this redundancy. The DPs selected to satisfy these FRs, essentially control stations, are listed above. The designs fulfilling both pairs of FRs, respective local and remote control, incorporate common systems; for the rudder, a common hydraulic system and for the bow thruster, a common control air system. Because the local control FRs are fulfilled first, $DP_{2.2.1}$ additionally contributes to $FR_{2.2.2}$ and $DP_{2.3.2}$ additionally contributes to $FR_{2.3.3}$. Decomposition of $DP_{2.2.1}$and $DP_{2.3.2}$ progress to include these systems.

To ensure maneuverability to port and starboard ($FR_{2.3.1}$), the bow thruster is attached to the ship on a pivotal mount ($DP_{2.3.1}$). A conventional bow thruster is an electric driven pump used to accelerate and redirect the flow of water. As water discharges from this pump-like device, the bow moves in the direction opposite the discharge. $FR_{2.4.4}$ and $FR_{2.3.5}$ result because a conventional bow thruster is selected to fulfill $FR_{2.3}$. Naturally, the typical electrical connection, $DP_{2.3.4}$ and $DP_{2.3.5}$, is used.

Decomposing $DP_{2.2.1}$ and $DP_{2.3.2}$ completes the $FR_2$ branch. All other selected DPs are considered leaf nodes in this abbreviated decomposition. Once again, similar FR/DP sets result. These sets follow along with the design equations (Equations 3.34 and 3.35).

| | |
|---|---|
| $FR_{2.2.1.1}$ = Input desired rudder angle | $DP_{2.2.1.1}$ = Wheel |
| $FR_{2.2.1.2}$ = Display desired rudder angle | $DP_{2.2.1.2}$ = Indicator gage |
| $FR_{2.2.1.3}$ = Display actual rudder position | $DP_{2.2.1.3}$ = Rudder angle indicator |
| $FR_{2.2.1.4}$ = Produce desired rudder angle | $DP_{2.2.1.4}$ = Rudder hydraulic system |

$$\begin{Bmatrix} FR_{2.2.1.1} \\ FR_{2.2.1.2} \\ FR_{2.2.1.3} \\ FR_{2.2.1.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ x & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{2.2.1.1} \\ DP_{2.2.1.2} \\ DP_{2.2.1.3} \\ DP_{2.2.1.4} \end{Bmatrix} \tag{3.34}$$

$FR_{2.3.2.1}$ = Input desired thruster direction and power — $DP_{2.3.2.1}$ = Local control handle

$FR_{2.3.2.2}$ = Display input combination — $DP_{2.3.2.2}$ = Indicator gage

$FR_{2.3.2.3}$ = Produce desired direction / thrust combination — $DP_{2.3.2.3}$ = Thruster control air system

$$\begin{Bmatrix} FR_{2.3.2.1} \\ FR_{2.3.2.2} \\ FR_{2.3.2.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ x & O & X \end{bmatrix} \begin{Bmatrix} DP_{2.3.2.1} \\ DP_{2.3.2.2} \\ DP_{2.3.2.3} \end{Bmatrix} \tag{3.35}$$

The means to input the desired rudder angle ($FR_{2.2.1.1}$) is a wheel ($DP_{2.2.1.1}$), similar to car's steering wheel. The means to input the desired thruster direction and power ($FR_{2.3.2.1}$) is a local control handle ($DP_{2.3.2.1}$). Comparable methods of supplying inputs exist at the remote control stations as well. Displaying the actual rudder angle ($FR_{2.2.1.3}$) is required and fulfilled by the rudder angle indicator ($DP_{2.2.1.3}$). This requirement exists because the rudder does not instantaneously respond to an input. Therefore, operators need assurance that the rudder is responding and will ultimately produce the desired effect. An operator determines if the bow thruster is responding almost instantaneously by observing the thruster wake at the bow; thus negating the need for a similar indicating device. Neither the desired rudder angle ($FR_{2.2.1.4}$), nor the desired thruster combination ($FR_{2.3.2.3}$) is produced if either the wheel, or the local control handle are not properly calibrated. In other words, the desired input is not actually entered, but thought to be properly entered when reading the appropriate indicator gage ($DP_{2.2.1.2}$ and $DP_{2.3.2.2}$). The resulting effect is, therefore, different from the desired input. Because this potentially occurs, $DP_{2.2.1.1}$ and $DP_{2.3.2.1}$ somewhat affect $FR_{2.2.1.4}$ and

$FR_{2.3.2.3}$ (indicated by the lowercase $x$).

$FR_3$ and $DP_3$ are listed next. Complete decomposition of $DP_3$ produces the next portion of the design hierarchy. Equation 3.36 functionally links the first child level FR/DP pairs.

$FR_3$ = Neutralize enemy targets — $DP_3$ = Combat systems configuration

$FR_{3.1}$ = Detect targets — $DP_{3.1}$ = Ship's sensors

$FR_{3.2}$ = Classify targets — $DP_{3.2}$ = Surveillance systems with identification protocols

$FR_{3.3}$ = Engage targets — $DP_{3.3}$ = Weapons systems

$FR_{3.4}$ = Operate as "node" sharing information within system-of-systems — $DP_{3.4}$ = Combat systems networking protocol (NTDS, JMCIS, etc.)

$FR_{3.5}$ = Provide target prosecution flexibility — $DP_{3.5}$ = Embarked helicopter

$$\begin{Bmatrix} FR_{3.1} \\ FR_{3.2} \\ FR_{3.3} \\ FR_{3.4} \\ FR_{3.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ X & X & O & O & O \\ X & x & X & O & O \\ X & x & x & X & O \\ O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{3.1} \\ DP_{3.2} \\ DP_{3.3} \\ DP_{3.4} \\ DP_{3.5} \end{Bmatrix} \tag{3.36}$$

The individual components and systems comprising the ship's combat systems configuration ($DP_3$) are designed by combat systems (CS) engineers [21]. These engineers specialize in designing the complex electronics, electromechanical interfaces, and computer software collectively employed to neutralize enemy targets ($FR_3$). CS engineers also create and test the computer networking protocols ($DP_{3.4}$) used to transfer information between system-of-systems elements ($FR_{3.4}$).

Three distinct phases define the functional performance of the combat systems configuration. First, it must detect targets ($FR_{3.1}$) using installed ship's sensors ($DP_{3.1}$). Next, it must classify targets ($FR_{3.2}$) with surveillance systems including the necessary identification protocols ($DP_{3.2}$). Finally, if the target is deemed a threat, it must engage ($FR_{3.3}$) until the threat is mitigated using the actual weapons systems ($DP_{3.3}$). In order to provide additional target

prosecution flexibility ($FR_{3.5}$), whenever possible, an embarked helicopter ($DP_{3.5}$) equipped with its own weapons loadout is included in the combat systems configuration.

Since detection is the cornerstone of neutralizing threats, $DP_{3.1}$ contributes to the accomplishment of $FR_{3.2}$, $FR_{3.3}$, and $FR_{3.4}$. Positive identification prior to engagement is unquestionably the norm, but not necessarily required before engaging an unidentified contact operating in a threatening posture. Therefore weaker functional dependence is assigned to $DP_{3.2}$ with respect to fulfilling $FR_{3.3}$. Similarly, positive contact identification and engagement solution determination are desirable prior to transferring data to another system-of-systems node. Since these preferred data sets are not absolutely required, weaker functional dependence is assigned between $FR_{3.4}$ and both $DP_{3.2}$ and $DP_{3.3}$.

For the naval architect, combat systems are treated as fixed inputs to the ship design, so that interfacing physical parameters such as weight, volume, centers of gravity, arcs of fire, electromagnetic radiation interference, and sensor coverage ensure a properly designed physical total ship system. This study adopts the naval architect's perspective and not the CS engineer's point of view. Therefore, decomposition of the $DP_3$ sub-branches terminate whenever one of the components, assumed completely designed by CS engineers, is directly interjected. At this level of decomposition, both $DP_{3.4}$ and $DP_{3.5}$ meet this criterion. This analysis does not attempt to functionally design combat systems; although, an extensive decomposition functionally defining combat system requirements (limited by the naval architect's level of knowledge) is contained in Appendix B.

Decomposition of $DP_{3.1}$, ship's sensors, proceeds as follows. The four child FRs are fulfilled in an uncoupled manner by the selected DPs as shown in Equation 3.37.

| | |
|---|---|
| $FR_{3.1.1}$ = Detect surface and shore based targets | $DP_{3.1.1}$ = Surface search radar (2D) |
| $FR_{3.1.2}$ = Detect subsurface targets | $DP_{3.1.2}$ = Sonar |
| $FR_{3.1.3}$ = Detect airborne targets | $DP_{3.1.3}$ = Air search radar (3D) |
| $FR_{3.1.4}$ = Detect electromagnetic (EM) emissions | $DP_{3.1.4}$ = Electronic countermeasures (ECM) surveillance antennas |

$$\begin{Bmatrix} FR_{3.1.1} \\ FR_{3.1.2} \\ FR_{3.1.3} \\ FR_{3.1.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{3.1.1} \\ DP_{3.1.2} \\ DP_{3.1.3} \\ DP_{3.1.4} \end{Bmatrix} \tag{3.37}$$

A single radar cannot fulfill both $FR_{3.1.1}$, detect surface and shore based targets, and $FR_{3.1.3}$, detect airborne targets. A 2D surface search radar ($DP_{3.1.1}$) determines target bearing and range, which sufficiently defines a surface target. Whereas, these two pieces of information do not sufficiently define an airborne target, a third parameter, elevation, is also vital in defining an airborne target's position. Therefore, a 3D air search radar ($DP_{3.1.3}$) is selected to independently satisfy $FR_{3.1.3}$. Both radars are at the leaf level. Sonar ($DP_{3.1.2}$) is the means to detect subsurface targets ($FR_{3.1.2}$). $DP_{3.1.2}$ requires further decomposition. Another means of detecting operating units exploits emitted electromagnetic (EM) pulses. These EM emissions are detected ($FR_{3.1.4}$) by electronic countermeasures (ECM) surveillance antennas ($DP_{3.1.4}$) and analyzed. $DP_{3.1.4}$ is also a leaf node requiring no further decomposition.

The analysis of $DP_{3.1.2}$, sonar, yields two FRs. Equation 3.38 are the design equations showing the functional independence of the stated FRs resulting from the DPs selected.

| | |
|---|---|
| $FR_{3.1.2.1}$ = Detect subsurface contacts without additionally compromising position | $DP_{3.1.2.1}$ = Passive sonar (towed array "tail") |
| $FR_{3.1.2.2}$ = Detect subsurface contacts with compromising position | $DP_{3.1.2.2}$ = Active sonar (sonar dome) |

$$\begin{Bmatrix} FR_{3.1.2.1} \\ FR_{3.1.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP_{3.1.2.1} \\ DP_{3.1.2.2} \end{Bmatrix} \tag{3.38}$$

There are two methods of extracting contact data using sonar. The first method, passive sonar ($DP_{3.1.2.1}$), is less precise and more tedious, but enables the detection of subsurface contacts without additionally compromising the ship's position ($FR_{3.1.2.1}$). Passive sonar, as

its name states, is passively listening for acoustic signatures utilizing an array of hydrophones towed behind the ship. The second method, active sonar ($DP_{3.1.2.2}$) is very precise, but the ship's position is compromised while detecting subsurface contacts in this manner ($FR_{3.1.2.2}$). Active sonar uses dual purpose, transmit and receive, hydrophones usually mounted on a sonar dome. These hydrophones send out an acoustic pulse and a target is located based on the time it takes this pulse to travel to the target and return to the transmission source.

The next sub-branch requiring decomposition is $DP_{3.2}$, surveillance systems with identification protocols. Decomposition results in three FR/DP pairs functionally related by Equation 3.39. The three child level FRs are independently fulfilled by the selected DPs as indicated in the uncoupled design equations.

| | |
|---|---|
| $FR_{3.2.1}$ = Classify surface and airborne targets electronically | $DP_{3.2.1}$ = Identification friend / foe (IFF) system |
| $FR_{3.2.2}$ = Classify subsurface targets | $DP_{3.2.2}$ = Passive sonar signature identification protocol |
| $FR_{3.2.3}$ = Classify EM emissions | $DP_{3.2.3}$ = EM signature identification library |

$$\begin{Bmatrix} FR_{3.2.1} \\ FR_{3.2.2} \\ FR_{3.2.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{bmatrix} \begin{Bmatrix} DP_{3.2.1} \\ DP_{3.2.2} \\ DP_{3.2.3} \end{Bmatrix} \tag{3.39}$$

Aircraft, and some military surface vessels, transmit characteristic electronic patterns for identification purposes. By exploiting these signals, surface and airborne targets are classified electronically ($FR_{3.2.1}$) using an identification friend/foe (IFF) system ($DP_{3.2.1}$). The IFF system is a mature design when inserted on to the ship; this system is at the leaf level. To the naval architect, the protocol used to evaluate passive sonar signatures ($DP_{3.2.2}$) is an ethereal component embedded in the sonar system. The EM signature identification library ($DP_{3.2.3}$) also manifests itself as a CS engineer developed software program. Therefore, $FR_{3.2.2}$ and $FR_{3.2.3}$ are fulfilled by CS engineers and require no further addressing by the naval architect making $DP_{3.2.2}$ and $DP_{3.2.3}$ leaf nodes.

The final decomposed $FR_3$ sub-branch is $DP_{3.3}$, weapons systems. Each child level FR

is satisfied by a DP such that a decoupled design results. These FR/DP sets and the design equations (Equation 3.40) follow.

$FR_{3.3.1}$ = Engage long range surface / shore based targets

$DP_{3.3.1}$ = Surface to surface / land attack missile system (Tomahawk)

$FR_{3.3.2}$ = Engage short range surface / shore based targets

$DP_{3.3.2}$ = Naval gun

$FR_{3.3.3}$ = Engage subsurface targets

$DP_{3.3.3}$ = Torpedo delivery system

$FR_{3.3.4}$ = Engage airborne targets

$DP_{3.3.4}$ = Surface to air missile system

$$\begin{Bmatrix} FR_{3.3.1} \\ FR_{3.3.2} \\ FR_{3.3.3} \\ FR_{3.3.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ x & X & O & O \\ O & O & X & O \\ x & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{3.3.1} \\ DP_{3.3.2} \\ DP_{3.3.3} \\ DP_{3.3.4} \end{Bmatrix} \tag{3.40}$$

Specific weapons systems are designed to engage specific target types as indicated in the above design equations. Weak functional dependence of $DP_{3.3.1}$ on $FR_{3.3.2}$ results because surface to surface missiles may also be used to engage short range surface and shore based targets. The preferred, and less costly, method is to engage these types of short range targets with a naval gun ($DP_{3.3.2}$), especially a gun which fires precision guided munitions. Additionally, weak dependence of $DP_{3.3.1}$ on $FR_{3.3.4}$ results due to the common design of missile storage and loading systems. Following current Navy design practice, vertical launch system (VLS) canisters house all missiles ($DP_{3.3.1}$ and $DP_{3.3.4}$) prior to launch. Also, a single crane loads all missiles regardless of type.

The decomposition process continues with $DP_4$, countermeasures methods. The applicable design constraints are restated followed by the child level FR/DP pairs. Equation 3.41, the design equations, begins the growth of this design hierarchy branch.

$FR_4$ = Protect from enemy attack

$DP_4$ = Countermeasures methods

$C_8$ =Total available volume $\geq$ Total required volume

$C_9$ = Total available arrangeable area $\geq$ Total required arrangeable area

$FR_{4.1}$ = Neutralize enemy weapon's effect by "hard kill" $DP_{4.1}$ = Self defense weapons

$FR_{4.2}$ = Neutralize enemy weapon's effect by "soft kill" $DP_{4.2}$ = Self defense decoys

$FR_{4.3}$ = Reduce likelihood of enemy detection $DP_{4.3}$ = Signatures reduction

$$\left\{ \begin{array}{c} FR_{4.1} \\ FR_{4.2} \\ FR_{4.3} \end{array} \right\} = \begin{bmatrix} X & O & O \\ x & X & O \\ O & O & X \end{bmatrix} \left\{ \begin{array}{c} DP_{4.1} \\ DP_{4.2} \\ DP_{4.3} \end{array} \right\} \tag{3.41}$$

Two terms, representing two very different phenomena, are commonly used to describe the neutralization of enemy weapons. The function neutralize enemy weapon's effect by "hard kill" ($FR_{4.1}$) requires a self defense weapon ($DP_{4.1}$) to physically strike and disable the incoming threat. The function neutralize enemy weapon's effect by "soft kill" ($FR_{4.2}$) does not require a physical engagement, but rather requires confusing the incoming weapon's targeting protocol. The primary means to accomplish this is by deploying a self defense decoy ($DP_{4.2}$). Also, $DP_{4.1}$ may cause a soft kill if the threat weapon acquires the weapon launched to destroy it. Designing in methods to reduce the likelihood of enemy detection ($FR_{4.3}$) contributes significantly to self defense. Since there are various detection techniques, the broad parameter termed signatures reduction ($DP_{4.3}$) satisfies the stated FR. Further decomposition covers this aspect in greater detail.

All child level DPs require additional decomposition starting with $DP_{4.1}$. The $FR_{4.1}$ sub-branch addresses the methods of actively countering enemy threats. Only airborne threats are handled actively for this design. The FR/DP pairs germane to the decomposition are stated below with Equation 3.42, the design equations mapping functional to physical relationships.

$FR_{4.1.1}$ = Neutralize long range airborne weapon (missile) $DP_{4.1.1}$ = Long range surface to air missile system (Nato Sea Sparrow)

$FR_{4.1.2}$ = Neutralize medium range airborne weapon (missile) $DP_{4.1.2}$ = Medium range surface to air missile system (Rolling Airframe Missile)

$FR_{4.1.3}$ = Neutralize short range airborne weapon (missile) — $DP_{4.1.3}$ = Close in weapons system (CIWS)

$$\begin{Bmatrix} FR_{4.1.1} \\ FR_{4.1.2} \\ FR_{4.1.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ x & X & O \\ O & x & X \end{bmatrix} \begin{Bmatrix} DP_{4.1.1} \\ DP_{4.1.2} \\ DP_{4.1.3} \end{Bmatrix} \tag{3.42}$$

This design follows the traditional layered self defense strategy for engaging airborne threats. The FRs address neutralizing airborne threats at three distinct ranges, that is long ($FR_{4.1.1}$), medium ($FR_{4.1.2}$), and short range ($FR_{4.1.3}$). All the DPs responding to each respective FR are types of self defense weapons systems that engage at specified ranges. Because it is desirable to overlap engagement envelopes, i.e. long and medium range weapons coverage overlaps at the transition from long to medium range, $DP_{4.1.1}$ contributes to $FR_{4.1.2}$ and $DP_{4.1.2}$ contributes to $FR_{4.1.3}$.

The $FR_{4.2}$ sub-branch addresses countering enemy threats by confusing the systems designed to acquire targets. Five FRs are developed to further functionally define these needs. These FRs along with the accompanying DPs follow with Equation 3.43, the design equations.

$FR_{4.2.1}$ = Neutralize acoustic targeted weapons — $DP_{4.2.1}$ = Deployable noisemakers (Nixie)

$FR_{4.2.2}$ = Neutralize home on EM weapons — $DP_{4.2.2}$ = Electronic countercountermeasures (ECCM)

$FR_{4.2.3}$ = Neutralize home on IR weapons — $DP_{4.2.3}$ = Deployable IR decoys (Torch)

$FR_{4.2.4}$ = Neutralize home on object weapons — $DP_{4.2.4}$ = Deployable false targets (Chaf)

$$\begin{Bmatrix} FR_{4.2.1} \\ FR_{4.2.2} \\ FR_{4.2.3} \\ FR_{4.2.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{4.2.1} \\ DP_{4.2.2} \\ DP_{4.2.3} \\ DP_{4.2.4} \end{Bmatrix} \tag{3.43}$$

By using a deployable noisemakers, for example Nixie ($DP_{4.2.1}$), acoustic targeted torpe-

does may be neutralized ($FR_{4.2.1}$) by acquiring this false target. $FR_{4.2.2} - FR_{4.2.4}$ apply to neutralizing airborne weapons designed to respectively target EM radiation, IR signatures, and physical targets. $DP_{4.2.2} - DP_{4.2.4}$ are used to "soft kill" each type of guided weapon by hindering, or confusing, the appropriate targeting system. All these DPs are leaf nodes excluding $DP_{4.2.2}$.

Certain weapons engage on preprogrammed EM frequencies. A means of determining these frequencies, and then "jamming" the EM spectrum with high intensity radiated pulses can result in threat neutralization. This technique is commonly referred to as ECCM, electronic countercountermeasures ($DP_{4.2.2}$). The resulting decomposition follows with the design equations, Equation 3.44.

| | |
|---|---|
| $FR_{4.2.2.1}$ = Determine EM frequency being targeted | $DP_{4.2.2.1}$ = Computer |
| $FR_{4.2.2.2}$ = Select respective EM frequency to be jammed | $DP_{4.2.2.2}$ = Frequency selection protocol |
| $FR_{4.2.2.3}$ = Jam respective EM spectrum range | $DP_{4.2.2.3}$ = Antenna emitting high intensity EM pulse |
| $FR_{4.2.2.4}$ = Receive electrical power | $DP_{4.2.2.4}$ = Electrical hardwire connection point |
| $FR_{4.2.2.5}$ = Energize / de-energize | $DP_{4.2.2.5}$ = Control panel |

$$\begin{Bmatrix} FR_{4.2.2.1} \\ FR_{4.2.2.2} \\ FR_{4.2.2.3} \\ FR_{4.2.2.4} \\ FR_{4.2.2.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & O & X & O & O \\ O & O & O & X & O \\ O & O & O & X & X \end{bmatrix} \begin{Bmatrix} DP_{4.2.2.1} \\ DP_{4.2.2.2} \\ DP_{4.2.2.3} \\ DP_{4.2.2.4} \\ DP_{4.2.2.5} \end{Bmatrix} \tag{3.44}$$

CS engineers design the system components fulfilling all fourth tier FRs. As such, for this design, the naval architect's only concern is placing the components on the concept ship without further design or decomposition. The only coupling between these FRs and DPs results from using the typical electrical connection; $DP_{4.2.2.4}$ contributes to the satisfaction of $FR_{4.2.2.5}$.

The $FR_{4.3}$ sub-branch addresses the methods of avoiding enemy detection. Since adversaries

possess multiple means of detecting ships, $DP_{4.3}$ requires further decomposition. The FR/DP sets beginning this further refinement and the design equations (Equation 3.45) follow.

$FR_{4.3.1}$ = Reduce detection by acoustic sensing means — $DP_{4.3.1}$ = Acoustic masking and vibration damping

$FR_{4.3.2}$ = Reduce detection by electromagnetic (EM) sensing means — $DP_{4.3.2}$ = Exploitation of radar EM pulse characteristics

$FR_{4.3.3}$ = Reduce detection by infrared (IR) sensing means — $DP_{4.3.3}$ = Dissipation of heat sources

$FR_{4.3.4}$ = Reduce detection by EM surveillance means — $DP_{4.3.4}$ = EM radiation control (EMCON conditions)

$FR_{4.3.5}$ = Reduce detection by magnetic field actuated ordnance — $DP_{4.3.5}$ = Degaussing system

$$\begin{Bmatrix} FR_{4.3.1} \\ FR_{4.3.2} \\ FR_{4.3.3} \\ FR_{4.3.4} \\ FR_{4.3.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & O & X & O & O \\ O & O & O & X & O \\ O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{4.3.1} \\ DP_{4.3.2} \\ DP_{4.3.3} \\ DP_{4.3.4} \\ DP_{4.3.5} \end{Bmatrix} \tag{3.45}$$

The third tier FRs address the functions associated with being detected by the enemy and being acquired by weapons. A target is located and targeted by exploiting one of the five major signatures; thus $FR_{4.3.1} - FR_{4.3.5}$. Of course, visual recognition is also a valid method of detection. $DP_{4.3.1} - DP_{4.3.5}$ identify the methods used to reduce the various signatures. All these DPs are design considerations, except EM radiation control ($DP_{4.3.4}$) which is an operational posture. Setting EMCON conditions define the extent of acceptable electromagnetic radiation discharge. By imposing stringent standards, minimal radiation leaves the ship, therefore operationally fulfilling $FR_{4.3.4}$ without additional discussion. $DP_{4.3.5}$, the degaussing system, exists as a leaf node and requires no additional decomposition.

$DP_{4.3.1}$, acoustic masking and vibration damping, fulfills $FR_{4.3.1}$, reduce detection by acoustic sensing means. $DP_{4.3.1}$ is refined by determining the functions it must fulfill. These FRs are listed along with the selected DPs. Equation 3.46 maps the FR/DP relationships.

$FR_{4.3.1.1}$ = Mask propeller noise

$FR_{4.3.1.2}$ = Mask hull noise

$FR_{4.3.1.3}$ = Absorb vibrations

$FR_{4.3.1.4}$ = Absorb engine vibrations (specifically)

$DP_{4.3.1.1}$ = Prairie system

$DP_{4.3.1.2}$ = Masker system

$DP_{4.3.1.3}$ = Vibration absorbent decks (rubber matting)

$DP_{4.3.1.4}$ = Vibration absorbent mounts

$$\left\{ \begin{array}{c} FR_{4.3.1.1} \\ FR_{4.3.1.2} \\ FR_{4.3.1.3} \\ FR_{4.3.1.4} \end{array} \right\} = \begin{bmatrix} X & O & O & O \\ X & X & O & O \\ O & O & X & O \\ O & O & x & X \end{bmatrix} \left\{ \begin{array}{c} DP_{4.3.1.1} \\ DP_{4.3.1.2} \\ DP_{4.3.1.3} \\ DP_{4.3.1.4} \end{array} \right\} \tag{3.46}$$

$FR_{4.3.1.1}$ and $FR_{4.3.1.2}$ pertain to the acoustic masking portion, while $FR_{4.3.1.3}$ and $FR_{4.3.1.4}$ pertain to the vibration damping portion of $DP_{4.3.1}$. Both the prairie system ($DP_{4.3.1.1}$) and the masker system ($DP_{4.3.1.2}$) use pressurized air to mask acoustic signatures which are attributed to specific ship types. By strategically injecting air, these acoustic signatures are effectively disguised. Since both systems share the same air source and the prairie system is designed first, $DP_{4.3.1.1}$ contributes to $FR_{4.3.1.2}$. Vibrations, specifically those vibrations associated with machinery operations, transmit through the hull and into the surrounding water as acoustic energy. To absorb detrimental vibrations leading to transmitted noise ($FR_{4.3.1.3}$ and $FR_{4.3.1.4}$), vibration absorbent decks ($DP_{4.3.1.3}$) and mounts ($DP_{4.3.1.4}$) are incorporated into the design. Absorbent mounts primarily mitigate engine vibrations, but rubber matting somewhat contributes to satisfying the function. (as indicated by a lowercase $x$ in the design equations).

The $FR_{4.3.2}$ sub-branch is next defined. Substantial efforts developing ways to fulfill $FR_{4.3.2}$, reduce detection by electromagnetic (EM) sensing means, have been expended, mostly in the recent past. The introduction of technologies that aid in the exploitation of radar EM pulse characteristics ($DP_{4.3.2}$) is the method of choice. Equation 3.47 defines the fulfillment of the stated decomposed FRs by the selected DPs.

$FR_{4.3.2.1}$ = Minimize radar cross section (RCS) $DP_{4.3.2.1}$ = Superstructure construction

$FR_{4.3.2.2}$ = Cause radar EM pulse to not return to source $DP_{4.3.2.2}$ = Radar absorbent material (RAM) applied to superstructure

$$\left\{ \begin{array}{c} FR_{4.3.2.1} \\ FR_{4.3.2.2} \end{array} \right\} = \left[ \begin{array}{cc} X & O \\ O & X \end{array} \right] \left\{ \begin{array}{c} DP_{4.3.2.1} \\ DP_{4.3.2.2} \end{array} \right\} \tag{3.47}$$

The decomposed FRs were first conceived by evaluating the radar-evading performance of aircraft. These aircraft functions were naturally extended to enhance ship survivability. $FR_{4.3.2.1}$, minimize radar cross section (RCS), is satisfied by $DP_{4.3.2.1}$, superstructure construction. The specific characteristics of the construction are defined as decomposition advances. To maintain a decoupled design, as discussed previously, hull construction is not manipulated to minimize the RCS. $DP_{4.3.2.2}$, radar absorbent material (RAM) applied to superstructure, fulfills $FR_{4.3.2.2}$, cause radar EM pulse to not return to source. RAM technology originated in the aircraft industry and, in varying forms, is now applied to both aircraft and ships.

$DP_{4.3.2.1}$ requires further decomposition to define the specific functions that must be satisfied to ensure a reduced RCS. Three child FRs result and are satisfied by the specified DPs listed below. Equation 3.48 is the uncoupled design equations.

$FR_{4.3.2.1.1}$ = Redirect radar EM pulse $DP_{4.3.2.1.1}$ = Sloped superstructure sides

$FR_{4.3.2.1.2}$ = Reduce ship's frontal / side areas $DP_{4.3.2.1.2}$ = Superstructure arrangements/layout

$FR_{4.3.2.1.3}$ = Reduce structure that increases radar EM pulse reflective strength $DP_{4.3.2.1.3}$ = Di/trihedral elimination

$$\left\{ \begin{array}{c} FR_{4.3.2.1.1} \\ FR_{4.3.2.1.2} \\ FR_{4.3.2.1.3} \end{array} \right\} = \left[ \begin{array}{ccc} X & O & O \\ O & X & O \\ O & O & X \end{array} \right] \left\{ \begin{array}{c} DP_{4.3.2.1.1} \\ DP_{4.3.2.1.2} \\ DP_{4.3.2.1.3} \end{array} \right\} \tag{3.48}$$

The radar cross section is determined by the EM pulse strength returned to the source. The three FRs express the possible ways to reduce the return pulse strength. If a pulse hits

a target, but does not return to the source, the target does not exist to the radar. Thus, $FR_{4.3.2.1.1}$, redirect radar EM pulse, exists and is satisfied by $DP_{4.3.2.1.1}$, sloped superstructure sides. A radar pulse must contact the ship superstructure before returning to the source. The probability of this occurring decreases by fulfilling $FR_{4.3.2.1.2}$, reduce ship's frontal / side areas, with $DP_{4.3.2.1.2}$, superstructure arrangements/layout, and remaining cognizant of the goal. Finally, certain features, specifically dihedrals and trihedrals, actually increase the EM pulse reflective strength when hit. Therefore, $FR_{4.3.2.1.3}$, reduce structure that increases radar EM pulse reflective strength, is fulfilled by $DP_{4.3.2.1.3}$, di/trihedral elimination.

Two like FRs result from decomposing $DP_{4.3.2.1.2}$. Additionally, both FRs are satisfied similarly and have similar additional design constraints. This FR/ DP set is listed with the respective design equations (Equation 3.49).

| | |
|---|---|
| $FR_{4.3.2.1.2.1}$ = Enclose helicopter | $DP_{4.3.2.1.2.1}$ = Aircraft hanger |
| $FR_{4.3.2.1.2.2}$ = Enclose personnel and equipment | $DP_{4.3.2.1.2.2}$ = Deckhouse |

$C_{8.1}$ = Available hanger volume $\geq$ Required hanger volume

$C_{9.1}$ = Available hanger arrangeable area $\geq$ Required hanger area

$C_{8.2}$ = Available deckhouse volume $\geq$ Required deckhouse volume

$C_{9.2}$ = Available arrangeable deckhouse area $\geq$ Required deckhouse area

$$\begin{Bmatrix} FR_{4.3.2.1.2.1} \\ FR_{4.3.2.1.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ x & X \end{bmatrix} \begin{Bmatrix} DP_{4.3.2.1.2.1} \\ DP_{4.3.2.1.2.2} \end{Bmatrix} \tag{3.49}$$

The superstructure arrangements/layout ($DP_{4.3.2.1.2}$) decompose to include two functional requirements, both pertaining to enclosing of ship entities. Because the function of enclosing specific items leads to space requirements, the four 'sub-constraints' are defined. $DP_{4.3.2.1.2.1}$ contributes to $FR_{4.3.2.1.2.2}$ because the aircraft hanger also encloses personnel and equipment. But, enclosing the helicopter ($FR_{4.3.2.1.2.1}$) is the primary purpose to design a hanger. Therefore, only weak functional dependence is assigned to this relationship. The deckhouse ($DP_{4.3.2.1.2.2}$) exists exclusively to fulfill $FR_{4.3.2.1.2.2}$ in this context.

The two decompositions leading to the final tier in the $FR_{4.3.2}$ sub-sub-branch are discussed

concurrently because of similarity. In fact, only a slight difference separates the two. Both sets of FR/DP pairs are listed with the two uncoupled design equations (Equations 3.50 and 3.51).

$FR_{4.3.2.1.2.1.1}$ = Ensure watertight integrity $DP_{4.3.2.1.2.1.1}$ = Structure

$FR_{4.3.2.1.2.1.2}$ = Allow vertical clearance for helicopter $DP_{4.3.2.1.2.1.2}$ = Hanger deck height

$$\left\{ \begin{array}{c} FR_{4.3.2.1.2.1.1} \\ FR_{4.3.2.1.2.1.2} \end{array} \right\} = \left[ \begin{array}{cc} X & O \\ O & X \end{array} \right] \left\{ \begin{array}{c} DP_{4.3.2.1.2.1.1} \\ DP_{4.3.2.1.2.1.2} \end{array} \right\} \tag{3.50}$$

$FR_{4.3.2.1.2.2.1}$ = Ensure watertight integrity $DP_{4.3.2.1.2.2.1}$ = Structure

$FR_{4.3.2.1.2.2.2}$ = Allow vertical clearance for personnel and equipment $DP_{4.3.2.1.2.2.2}$ = Number of decks and average height

$$\left\{ \begin{array}{c} FR_{4.3.2.1.2.2.1} \\ FR_{4.3.2.1.2.2.2} \end{array} \right\} = \left[ \begin{array}{cc} X & O \\ O & X \end{array} \right] \left\{ \begin{array}{c} DP_{4.3.2.1.2.2.1} \\ DP_{4.3.2.1.2.2.2} \end{array} \right\} \tag{3.51}$$

The structure ($DP_{4.3.2.1.2.1.1}$ and $DP_{4.3.2.1.2.2.1}$) ensures watertight integrity of the hanger and the deckhouse ($FR_{4.3.2.1.2.1.1}$ and $FR_{4.3.2.1.2.2.1}$). The aircraft hanger requires only one level of vertical clearance for the helicopter ($FR_{4.3.2.1.2.1.2}$) satisfied by designing an acceptable hanger deck height ($DP_{4.3.2.1.2.1.2}$). Whereas, in the deckhouse, several decks are required to allow vertical clearance for personnel and equipment ($FR_{4.3.2.1.2.2.2}$). This FR is similarly satisfied with an average deck height, but also includes the appropriate number of decks ($DP_{4.3.2.1.2.2.2}$) spaced to use the entire deckhouse height efficiently.

Many weapons target infrared (heat) signatures. Therefore, another FR regarding signatures reduction is derived as $FR_{4.3.3}$, reduce detection by IR sensing means. Since heat sources exist and it is unlikely that they will be eliminated altogether, the DP satisfying this FR becomes the dissipation of heat sources ($DP_{4.3.3}$). Two FRs that are satisfied in the uncoupled manner shown in Equation 3.52 result from the decomposition process.

$FR_{4.3.3.1}$ = Dissipate engine exhaust heat $DP_{4.3.3.1}$ = Stack boundary layer infrared suppression system (BLISS)

$FR_{4.3.3.2}$ = Dissipate general space heat $DP_{4.3.3.2}$ = Ventilation insulation

$$\begin{Bmatrix} FR_{4.3.3.1} \\ FR_{4.3.3.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP_{4.3.3.1} \\ DP_{4.3.3.2} \end{Bmatrix} \tag{3.52}$$

The burning of fuel creates hot exhaust gases. The release of these gases into the atmosphere contributes significantly to a ship's IR signature. A relatively new system designed to dissipate engine exhaust heat ($FR_{4.3.3.1}$), the stack boundary layer infrared suppression system (BLISS) ($DP_{4.3.3.1}$), mixes ambient air with exhaust gases to significantly reduce the heat of the released gases. Heat sources exist throughout the ship which are not as intense as those created by the burning of fuel. Air is always circulating within the ship using the ventilation system. To dissipate general space heat ($FR_{4.3.3.2}$), insulation is installed in ventilation ducting ($DP_{4.3.3.2}$). With this explanation ends the growth of $FR_4$ branch.

$DP_5$, support / auxiliary systems, satisfies $FR_5$, conduct sustained underway operations. $C_6$ and $C_9$ must be considered during satisfaction of this FR because generation of electrical power is one of the ship's vital support / auxiliary systems. Similarly, $C_{12}$, carry adequate fuel to transit endurance range at endurance speed, must also be considered while satisfying this FR because $DP_5$ also contains the fuel system. Before proceeding with formal decomposition, the items beginning the process are listed below.

$FR_5$ = Conduct sustained underway operations $DP_5$ = Support / Auxiliary systems

$C_7$ = Installed electrical power $\geq$ Required electrical power

$C_{10}$ = Incorporate design growth margins (weight, KG, and electrical power)

$C_{12}$ = Carry adequate fuel to transit endurance range at endurance speed

$DP_5$ must satisfies eight diverse functional requirements. Each of the these requirements must be fulfilled in order for the ship to operate as designed. Typically, the ship and crew spend a finite time in a port, debark the port to accomplish some operational commitment or training evolution, and then return to port (either the originally stated location, or a different

location). This in port/underway/return to port cycle repeatedly occurs throughout the ship's life cycle. Therefore, the listed FRs exist and are satisfied by the selected DPs. The diverse functions that $DP_5$ decomposes to fulfill are remarkably accomplished in an almost uncoupled fashion as indicated by the design equations, Equation 3.53.

| | |
|---|---|
| $FR_{5.1}$ = Ensure habitable conditions | $DP_{5.1}$ = Crew support / habitability features |
| $FR_{5.2}$ = Maintain equipment in operating condition | $DP_{5.2}$ = Maintenance philosophy |
| $FR_{5.3}$ = Communicate information | $DP_{5.3}$ =Communications equipment |
| $FR_{5.4}$ = Combat damage | $DP_{5.4}$ = Damage control (DC) systems and equipment |
| $FR_{5.5}$ = Secure position while underway | $DP_{5.5}$ = Anchoring system |
| $FR_{5.6}$ = Secure position while in port | $DP_{5.6}$ = Mooring system |
| $FR_{5.7}$ = Provide electrical power | $DP_{5.7}$ = Electrical system |
| $FR_{5.8}$ = Provide fuel source | $DP_{5.8}$ = Fuel system |

$$\begin{Bmatrix} FR_{5.1} \\ FR_{5.2} \\ FR_{5.3} \\ FR_{5.4} \\ FR_{5.5} \\ FR_{5.6} \\ FR_{5.7} \\ FR_{5.8} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O & O & O \\ O & X & O & O & O & O & O & O \\ O & O & X & O & O & O & O & O \\ X & O & O & X & O & O & O & O \\ O & O & O & O & X & O & O & O \\ O & O & O & O & O & X & O & O \\ O & O & O & O & O & O & X & O \\ O & O & O & O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{5.1} \\ DP_{5.2} \\ DP_{5.3} \\ DP_{5.4} \\ DP_{5.5} \\ DP_{5.6} \\ DP_{5.7} \\ DP_{5.8} \end{Bmatrix} \tag{3.53}$$

The FRs and DPs listed above are not extensively discussed at this point. At the next level of the design process, each FR/DP pair is introduced and then the DP is decomposed. The only coupled relationship occurs between $DP_{5.1}$ and $FR_{5.4}$. This coupling is not apparent until $DP_{5.1}$ is further refined. As stated previously, design decisions at higher levels affect the selection of DPs at lower levels. In this instance, the opposite applies. That is, decisions made

at lower levels must also be reflected in higher level design equations to accurately account for couplings during all design stages. Since an independent system to desmoke spaces is not desired, and the ship's ventilation system is used to fulfill this function, ultimately $DP_{5.1}$, crew support / habitability features (specifically, the ventilation system) contributes to $FR_{5.4}$, combat damage (specifically, desmoke spaces). For this abbreviated decomposition, $DP_{5.5}$, anchoring system, and $DP_{5.6}$, mooring system, are at the leaf level.

The existence of personnel on the ship leads to $FR_{5.1}$, ensure habitable conditions, which is fulfilled by $DP_{5.1}$, crew support / habitability features. The manning and automation decisions made throughout the design process influence the characteristics of the selected DPs. The applicable FR/DP pairs and design equations, Equation 3.54, follow with more in depth discussion focusing on the functional couplings.

$FR_{5.1.1}$ = Supply stores (food) sufficient to feed the crew for stores period — $DP_{5.1.1}$ = Provisions loadout

$FR_{5.1.2}$ = Supply fresh water — $DP_{5.1.2}$ = Potable water system

$FR_{5.1.3}$ = Control climate for crew comfort and machinery performance — $DP_{5.1.3}$ = Climate control system

$FR_{5.1.4}$ = Provide for crew hygiene — $DP_{5.1.4}$ = Plumbing system

$FR_{5.1.5}$ = Support feeding of crew — $DP_{5.1.5}$ = Food service equipment

$FR_{5.1.6}$ = Illuminate spaces — $DP_{5.1.6}$ = Lighting system

$FR_{5.1.7}$ = Allow crew escape when necessary — $DP_{5.1.7}$ = Life boats

$$\begin{Bmatrix} FR_{5.1.1} \\ FR_{5.1.2} \\ FR_{5.1.3} \\ FR_{5.1.4} \\ FR_{5.1.5} \\ FR_{5.1.6} \\ FR_{5.1.7} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O & O \\ O & X & O & O & O & O & O \\ O & X & X & O & O & O & O \\ O & X & X & X & O & O & O \\ X & X & X & X & X & O & O \\ O & O & O & O & O & X & O \\ O & O & O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{5.1.1} \\ DP_{5.1.2} \\ DP_{5.1.3} \\ DP_{5.1.4} \\ DP_{5.1.5} \\ DP_{5.1.6} \\ DP_{5.1.7} \end{Bmatrix} \tag{3.54}$$

Ship's have a finite amount of food storage capacity. Therefore, this storage space directly

affects the time period a ship can operate unsupported. If the crew does not receive proper nourishment, productivity decreases accordingly. This requirement manifests in $FR_{5.1.1}$, supply stores (food) sufficient to feed the crew for stores period. The stores period specifies the number of days the crew can operate without requiring an additional provisions loadout ($DP_{5.1.1}$). Along with food, the crew requires fresh water ($FR_{5.1.2}$). Some systems also require fresh water produced and provided by the potable water system ($DP_{5.1.2}$). As shown in the design equations, the climate control system ($DP_{5.1.3}$), plumbing system ($DP_{5.1.4}$), and food service equipment ($DP_{5.1.5}$), respectively fulfilling $FR_{5.1.3}$, $FR_{5.1.4}$, and $FR_{5.1.5}$ all depend on the potable water system. To supply hot water for washing of personnel, $DP_{5.1.3}$ (which includes auxiliary boilers) affects $FR_{5.1.4}$. $DP_{5.1.3}$ also contributes to $FR_{5.1.5}$ because hot water is also necessary to sanitize food contaminated items. Additionally, $FR_{5.1.5}$ is affected by $DP_{5.1.1}$, the food which actually feeds the crew, and $DP_{5.1.4}$, the means to remove the sanitizing water. The last two child FRs, $FR_{5.1.6}$ and $FR_{5.1.7}$ are affected only by the chosen DPs. All DPs at this level, except , $DP_{5.1.3}$ are leaf nodes.

$DP_{5.1.3}$, the climate control system, decomposes to fulfill six specific functions. The FR/DP sets and design equations are given below. The selected DPs satisfy all requirements in an uncoupled fashion as shown in Equation 3.55.

| | |
|---|---|
| $FR_{5.1.3.1}$ = Recirculate/replenish air within space | $DP_{5.1.3.1}$ = Ventilation system |
| $FR_{5.1.3.2}$ = Heat ship spaces | $DP_{5.1.3.2}$ = Steam system |
| $FR_{5.1.3.3}$ = Cool ship spaces | $DP_{5.1.3.3}$ = Chill water system |
| $FR_{5.1.3.4}$ = Maintain humidity level | $DP_{5.1.3.4}$ = Dehumidifier |
| $FR_{5.1.3.5}$ = Determine space temperature | $DP_{5.1.3.5}$ = Thermometer |
| $FR_{5.1.3.6}$ = Set desired space temperature | $DP_{5.1.3.6}$ = Thermostat |

$$\begin{Bmatrix} FR_{5.1.3.1} \\ FR_{5.1.3.2} \\ FR_{5.1.3.3} \\ FR_{5.1.3.4} \\ FR_{5.1.3.5} \\ FR_{5.1.3.6} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O \\ O & X & O & O & O & O \\ O & O & X & O & O & O \\ O & O & O & X & O & O \\ O & O & O & O & X & O \\ O & O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{5.1.3.1} \\ DP_{5.1.3.2} \\ DP_{5.1.3.3} \\ DP_{5.1.3.4} \\ DP_{5.1.3.5} \\ DP_{5.1.3.6} \end{Bmatrix} \tag{3.55}$$

$DP_{5.1.3.1}$, the ventilation system, satisfies $FR_{5.1.3.1}$, recirculate/replenish air within space. This requirement results not only from crew comfort concerns, but also from safety concerns. That is, to prevent the accumulation of potentially toxic gases in confined spaces. As stated earlier, $DP_{5.1.3.1}$ also desmokes spaces. $FR_{5.1.3.2}$ and $FR_{5.1.3.4}$ are functions relating to crew comfort and machinery operation. Specifically, the chill water system ($DP_{5.1.3.3}$) and dehumidifiers ($DP_{5.1.3.4}$) are used to ensure acceptable operating conditions for large electronic systems that generate heat. No further discussion accompanies the remaining three FR/DP pairs and decomposition of the $FR_{5.1}$ sub-branch terminates here.

A naval surface combatant is comprised of numerous systems and components designed to satisfy an extensive set of functional requirements. For a given ship to perform missions satisfactorily, $FR_{5.2}$, maintain equipment in operating condition, must be achieved. An underlying maintenance philosophy ($DP_{5.2}$) is implemented to ensure equipment remains functional. This philosophy can be decomposed as follows. The leaf nodes are defined by the design equations, Equation 3.56.

| | |
|---|---|
| $FR_{5.2.1}$ = Monitor equipment operation | $DP_{5.2.1}$ = Watchstanders / Automated machines / Combination |
| $FR_{5.2.2}$ = Repair equipment when necessary | $DP_{5.2.2}$ = Trained technicians (ship's crew / shore based) |
| $FR_{5.2.3}$ = Provide required repair parts | $DP_{5.2.3}$ = Supply repair parts inventory |
| $FR_{5.2.4}$ = Ensure non-interrupted operation during repairs | $DP_{5.2.4}$ = Machinery redundancy |

$$\left\{\begin{array}{c} FR_{5.2.1} \\ FR_{5.2.2} \\ FR_{5.2.3} \\ FR_{5.2.4} \end{array}\right\} = \begin{bmatrix} X & O & O & O \\ x & X & O & O \\ O & O & X & O \\ X & O & O & X \end{bmatrix} \left\{\begin{array}{c} DP_{5.2.1} \\ DP_{5.2.2} \\ DP_{5.2.3} \\ DP_{5.2.4} \end{array}\right\} \tag{3.56}$$

This decomposition is vital to the upcoming manning versus automated machinery study. At the onset of the design process, the design team must determine the means to satisfy $FR_{5.2.1}$, monitor equipment operation. $DP_{5.2.1}$, watchstanders / automated machines / combination (of both watchstanders and automated machinery) are the possible ways to satisfy the FR. Advantages and disadvantages exist when each DP is selected. Once monitoring determines a particular piece of machinery is malfunctioning, two options are presented. First, the piece of equipment could be repaired ($FR_{5.2.2}$) by onboard trained technicians ($DP_{5.2.2}$). Or, the machinery posture could be altered, such that the malfunctioning machinery is taken 'off line,' and a similarly capable piece of machinery is brought 'on line.' The inoperational item may then be repaired by shore based trained technicians ($DP_{5.2.2}$). In order to fulfill non-interrupted operation while awaiting repairs ($FR_{5.2.4}$), machinery redundancy ($DP_{5.2.4}$), in the form of parallel vice series configurations, must be incorporated. $DP_{5.2.1}$ contributes to $FR_{5.2.4}$ because the monitoring watchstanders, or machines, physically make this modification. Because repairs are often time critical, the ship must possess the capability to provide required repair parts ($FR_{5.2.3}$). An onboard supply repair parts inventory ($DP_{5.2.3}$) strives to meet this requirement.

The world today is experiencing the 'information age.' Information is key to success in many aspects of daily life. This applies equally to life at sea when conducting shipboard operations. Therefore, $FR_{5.3}$, communicate information, is an important requirement fulfilled by $DP_{5.3}$, communications equipment. Two levels of decomposition define the entire sub-branch for the purposes of this compact decomposition. The first FR/DP set and design equations (Equation 3.57) are given, followed by the second set of information (including Equation 3.58).

$FR_{5.3.1}$ = Communicate with external units    $DP_{5.3.1}$ = Transmit and receive antennas

$FR_{5.3.2}$ = Communicate internally

$DP_{5.3.2}$ = Internal communications (IC) equipment

$$\left\{ \begin{array}{c} FR_{5.3.1} \\ FR_{5.3.2} \end{array} \right\} = \left[ \begin{array}{cc} X & O \\ O & X \end{array} \right] \left\{ \begin{array}{c} DP_{5.3.1} \\ DP_{5.3.2} \end{array} \right\} \tag{3.57}$$

$FR_{5.3.1.1}$ = Communicate with other ships, commercial or navy (voice)

$DP_{5.3.1.1}$ = Bridge-to-bridge radio

$FR_{5.3.1.2}$ = Communicate with other navy units, ships or shorebased

$DP_{5.3.1.2}$ = Radio room equipment

$$\left\{ \begin{array}{c} FR_{5.3.1.1} \\ FR_{5.3.1.2} \end{array} \right\} = \left[ \begin{array}{cc} X & O \\ O & X \end{array} \right] \left\{ \begin{array}{c} DP_{5.3.1.1} \\ DP_{5.3.1.2} \end{array} \right\} \tag{3.58}$$

Information is passed via voice, printed text, or electronic (digital) data. Information in these forms must be communicated with external units ($FR_{5.3.1}$) and within the confines of the ship ($FR_{5.3.2}$). $DP_{5.3.1}$, transmit and receive antennas, is the basis of communicating with external units. A necessary means used to communicate voice transmissions to other navy ships or commercial vessels ($FR_{5.3.1.1}$) is the bridge-to-bridge VHF radio ($DP_{5.3.1.1}$). A broadly defined design parameter, radio room equipment ($DP_{5.3.1.2}$) allows secure and non-secure communications with other navy units ($FR_{5.3.1.2}$) in the form of voice, text, or data. Various forms of internal communications (IC) equipment including, telephone and computer networks, ($DP_{5.3.2}$) enable shipboard personnel to share information internally ($FR_{5.3.2}$).

When operating at sea, shipboard personnel are rarely given the opportunity to contact outside emergency response agencies to assist when casualties arise. Therefore, methods for controlling all types of damage ($FR_{5.4}$) are designed into every naval combatant. These methods are grouped together and called damage control (DC) systems and equipment ($DP_{5.4}$). The first level child FRs and DPs are listed below. Equation 3.59, the design equations, indicates that the selected DPs satisfy these FRs in a completely uncoupled manner. No further explanation of these FR/DP pairs follows. Only $DP_{5.5.1}$, fire fighting systems requires additional decomposition, primarily to describe the three types of fires typically encountered and the DPs

selected as extinguishing systems.

$FR_{5.4.1}$ = Fight fires

$FR_{5.4.2}$ = Control flooding

$FR_{5.4.3}$ = Repair hull damage

$FR_{5.4.4}$ = Display DC situation

$DP_{5.4.1}$ = Fire fighting systems

$DP_{5.4.2}$ = Dewatering systems

$DP_{5.4.3}$ = Hull repair resources

$DP_{5.4.4}$ = Damage Control Central situation display

$$\begin{Bmatrix} FR_{5.4.1} \\ FR_{5.4.2} \\ FR_{5.4.3} \\ FR_{5.4.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{5.4.1} \\ DP_{5.4.2} \\ DP_{5.4.3} \\ DP_{5.4.4} \end{Bmatrix} \tag{3.59}$$

$DP_{5.4.1}$ is decomposed to reach the final $FR_{5.4}$ sub-branch leaf level. The four resulting FRs are stated along with the respective DPs. The design equations are given in Equation 3.60.

$FR_{5.4.1.1}$ = Fight Class A fire

$FR_{5.4.1.2}$ = Fight Class B fire

$FR_{5.4.1.3}$ = Fight Class C fire

$FR_{5.4.1.4}$ = Desmoke space

$DP_{5.4.1.1}$ = Ship's Firemain

$DP_{5.4.1.2}$ = Aqueous film forming foam (AFFF) system

$DP_{5.4.1.3}$ = Fixed carbon dioxide ($CO_2$) system

$DP_{5.4.1.4}$ = Installed ventilation system

$$\begin{Bmatrix} FR_{5.4.1.1} \\ FR_{5.4.1.2} \\ FR_{5.4.1.3} \\ FR_{5.4.1.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ X & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{5.4.1.1} \\ DP_{5.4.1.2} \\ DP_{5.4.1.3} \\ DP_{5.4.1.4} \end{Bmatrix} \tag{3.60}$$

Class A fires burn solid objects, such as wood. Class A fires can be eliminated either by being smothered or by having the heat removed. The ship's firemain ($DP_{5.4.1.1}$) provides salt water to extinguish this classification of fire ($FR_{5.4.1.1}$). Class B fires a characterized by burning liquids, such as fuel oil. Class B fires must be smothered, i.e. a lack of oxygen extinguishes the

fire. An aqueous film forming foam (AFFF) system ($DP_{5.4.1.2}$) accomplishes $FR_{5.4.1.2}$, fight Class B fire. Because the AFFF must mix with firefighting water in the correct proportion to effectively smother the fire, $DP_{5.4.1.1}$ also contributes to $FR_{5.4.1.2}$. Class C fires are electrical fires. Like Class B fires, Class C fires must also be smothered. But, since salt water is a strong conductor, the AFFF system is not used to combat these fires ($FR_{5.4.1.3}$). For this design, a fixed carbon dioxide ($CO_2$) system ($DP_{5.4.1.3}$) provides the appropriate smothering agent for electrical fires. Upon extinguishing all fire types, the effected space must be desmoked ($FR_{5.4.1.4}$) with the installed ventilation system ($DP_{5.4.1.4}$).

$FR_{5.7}$, provide electrical power, is satisfied by $DP_{5.7}$, the electrical system. Decomposition reveals five additional child FRs. These FRs are fulfilled in a completely uncoupled manner by selecting the appropriate DPs. Equation 3.61 illustrates the stated uncoupled satisfaction of all FRs. No further discussion of the FR/DP pairs at this level of the design hierarchy follows. All selected DPs define the leaf level, except $DP_{5.8.1}$.

$FR_{5.7.1}$ = Generate electrical power — $DP_{5.7.1}$ = Ship's service generators

$FR_{5.7.2}$ = Generate electrical power in emergency situation — $DP_{5.7.2}$ = Emergency diesel generator

$FR_{5.7.3}$ = Distribute electrical power — $DP_{5.7.3}$ = Electrical switchboards

$FR_{5.7.4}$ = Transport electrical power to equipment — $DP_{5.7.4}$ = Cabling

$FR_{5.7.5}$ = Isolate equipment locally — $DP_{5.7.5}$ = Circuit breakers

$$\left\{\begin{array}{c} FR_{5.7.1} \\ FR_{5.7.2} \\ FR_{5.7.3} \\ FR_{5.7.4} \\ FR_{5.7.5} \end{array}\right\} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & O & X & O & O \\ O & O & O & X & O \\ O & O & O & O & X \end{bmatrix} \left\{\begin{array}{c} DP_{5.7.1} \\ DP_{5.7.2} \\ DP_{5.7.3} \\ DP_{5.7.4} \\ DP_{5.7.5} \end{array}\right\} \tag{3.61}$$

The ship's service generators ($DP_{5.7.1}$) are further decomposed. The applicable FR/DP sets are stated below with the design equations (Equation 3.62) mapping the functional to physical relationships.

$FR_{5.7.1.1}$ = Provide prime mover to turn rotor

$DP_{5.7.1.1}$ = Generator engines / turbines

$FR_{5.7.1.2}$ = Create electric field

$DP_{5.7.1.2}$ = Relative motion between rotor and stator

$$\begin{Bmatrix} FR_{5.7.1.1} \\ FR_{5.7.1.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{5.7.1.1} \\ DP_{5.7.1.2} \end{Bmatrix} \tag{3.62}$$

Electric field theory states that to create electricity ($FR_{5.7.1.2}$), an electrically conductive material, a magnetic field, and relative motion between the two ($DP_{5.7.1.2}$) are needed. The generator holds one of them, say the magnetic field, in a stationary position (called the stator) and provides the connection points to harness the created electricity. Each generator engine ($DP_{5.7.1.1}$) is a prime mover turning a conductive rotor ($FR_{5.7.1.1}$). Since there is no relative motion without the generator engine, $DP_{5.7.1.1}$ also contributes functionally to $FR_{5.7.1.2}$.

The generator engines ($DP_{5.7.1.1}$) are decomposed as the final portion of the $FR_{5.7}$ sub-branch definition. Five FRs must be accomplished supporting the operation of these engines / turbines. An additional sub-constraint ($C_{12.2}$) limits the selection of $DP_{5.7.1.1.2}$. The FR/DP pairs, the constraint, and the design equations given in Equation 3.63 follow.

$FR_{5.7.1.1.1}$ = Provide inertia to start engine

$DP_{5.7.1.1.1}$ = Starting air system

$FR_{5.7.1.1.2}$ = Provide fuel for continuous engine operation

$DP_{5.7.1.1.2}$ = GE fuel system

$FR_{5.7.1.1.3}$ = Cool engine

$DP_{5.7.1.1.3}$ = GE lube oil system

$FR_{5.7.1.1.4}$ = Provide air to support engine combustion

$DP_{5.7.1.1.4}$ = Engine inlet ducting

$FR_{5.7.1.1.5}$ = Remove combustion products

$DP_{5.7.1.1.5}$ = Engine exhaust ducting

$C_{12.2}$ = Fuel supply rate must support combined engine specific fuel consumption (sfc)

$$\begin{Bmatrix} FR_{5.7.1.1.1} \\ FR_{5.7.1.1.2} \\ FR_{5.7.1.1.3} \\ FR_{5.7.1.1.4} \\ FR_{5.7.1.1.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & O & X & O & O \\ O & O & O & X & O \\ O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{5.7.1.1.1} \\ DP_{5.7.1.1.2} \\ DP_{5.7.1.1.3} \\ DP_{5.7.1.1.4} \\ DP_{5.7.1.1.5} \end{Bmatrix} \tag{3.63}$$

The DPs satisfying $FR_{5.7.1.1.1} - FR_{5.7.1.1.5}$ are functionally independent. The functional mapping follows the same discussion explaining that of the MPE's. This explanation succeeds Equation 3.4. $C_{12.2}$ results because while transiting the endurance range, electrical power must also be provided. For this to happen, the generator engines require sufficient fuel over the entire endurance range.

The final decomposition resulting in the complete definition of the $FR_5$ branch (in abbreviated format) is the $FR_{5.8}$ sub-branch. Machinery onboard must be provided a fuel source ($FR_{5.8}$). For the design of this surface combatant, a traditional fuel system ($DP_{5.8}$) satisfies this FR. The FR/DP pairs and design equations, Equation 3.64 follow. This crude decomposition only addresses the primary functional requirements leading to leaf level definition.

| | |
|---|---|
| $FR_{5.8.1}$ = Onload fuel | $DP_{5.8.1}$ = Fuel onload system / Fueling at sea (FAS) system |
| $FR_{5.8.2}$ = Store fuel | $DP_{5.8.2}$ = Fuel storage system |
| $FR_{5.8.3}$ = Provide fuel for machinery operation | $DP_{5.8.3}$ = Fuel service system |

$$\begin{Bmatrix} FR_{5.8.1} \\ FR_{5.8.2} \\ FR_{5.8.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & X & X \end{bmatrix} \begin{Bmatrix} DP_{5.8.1} \\ DP_{5.8.2} \\ DP_{5.8.3} \end{Bmatrix} \tag{3.64}$$

Several factors influence the fuel system design. First, a method to onload fuel ($FR_{5.8.1}$) must be considered. For combatants that operate at great distances from home port for extensive time periods, a fueling at sea (FAS) system is required in addition to the standard in port fuel onload system ($DP_{5.8.1}$). The fuel storage system ($DP_{5.8.2}$) must be designed to hold fuel ($FR_{5.8.2}$) in sufficient quantity to satisfy $C_{12}$. Finally, including a method to provide

fuel for machinery operation ($FR_{5.8.3}$) completes the system design. The fuel service system ($DP_{5.8.3}$), which includes moving fuel from storage to the machinery, meets this requirement.

Hierarchial definition of the $FR_2$, $FR_3$, $FR_4$, and $FR_5$ branches is complete using a limited decomposition scheme. Therefore, the first through fifth branches of the design are now defined to all respective leaf levels. Conceptual design equations are formulated such that the entire decomposition thus far satisfies the Independence Axiom.

### 3.4.3 Fulfillment of $FR_6$

Following the sequential process outlined by the highest level design equations up to this point results in the design of all shipboard systems. The final step in the proposed process places these systems in a waterborne platform. This task highlights the naval architect's primary challenge. The real challenge of naval architecture is not designing the shipboard systems. It is the integrating all the systems into a feasible waterborne platform. Specifically, the hull form must be shaped sufficiently to hold all of these systems while floating upright in a stable equilibrium. Furthermore, the hull form designed to hold all systems must also be capable of traveling at a specified sustained speed. If the speed requirement is not attained, the hull form is not sufficient. Therefore the constraints placed on this final stage of the design are extremely important when selecting each respective DP. Once again, complete decomposition supporting manning and automation tradeoffs is not discussed for this final design branch.

Prior to continuing the decomposition process, $FR_6$, $DP_6$, and all applicable constraints are listed for quick reference.

$FR_6 =$ Operate on surface of water $\qquad DP_6 =$ Hull form

$C_1 =$ Initial acquisition cost $\leq \$\ XXM$ (say, \$ $750M$)

$C_2 =$ Average hourly operating cost $\leq \$\ XX$ (say, \$ $2,600/hr$)

$C_3 =$ Full load displacement $=$ Total weight

$C_4 =$ Ensure intact stability (GM $> 0$ ft)

$C_5 =$ Ensure acceptable transverse dynamic stability ($0.090 \leq GM/B \leq 0.122$)

$C_6 =$ Installed propulsive power $\geq$ Required propulsive power

$C_8 =$ Total available volume $\geq$ Total required volume

$C_9 =$ Total available arrangeable area $\geq$ Total required arrangeable area

$C_{10} =$ Incorporate design growth margins (weight, KG, propulsion and electrical power)

$C_{11} =$ Always operate at the design waterline (DWL)

$C_{12} =$ Carry adequate fuel to transit endurance range at endurance speed

The hull form is not a leaf node. Therefore, decomposition proceeds by determining the functions requiring accomplishment by $DP_6$. Appropriate DPs are selected to fulfill these first child level FRs. All but one of the highest level design constraints apply when satisfying $FR_6$. Each selected design parameter must achieve the desired functional requirement while simultaneously complying with the applicable constraints. If the constraints are not satisfied, another DP satisfying all criteria must be selected. The first child level FR/DP pairs follow with the devised decoupled design equations numbered as Equation 3.65

$FR_{6.1} =$ Enclose personnel and equipment $\quad DP_{6.1} =$ Hull

$FR_{6.2} =$ Support total ship weight $\quad DP_{6.2} =$ Displaced hull form volume

$FR_{6.3} =$ Minimize total resistance $\quad DP_{6.3} =$ Hull form characteristics (coefficients of form)

$$\begin{Bmatrix} FR_{6.1} \\ FR_{6.2} \\ FR_{6.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{6.1} \\ DP_{6.2} \\ DP_{6.3} \end{Bmatrix} \tag{3.65}$$

This decomposition defines the important required characteristics of a monohull hull form. The entire hull ($DP_{6.1}$), above and below the waterline, is analyzed during the hull design process because of the need to enclose all personnel and equipment ($FR_{6.1}$). The hull must meet or exceed the difference of both the required volume and the deckhouse volume, and the total area and the deckhouse area in order to comply with $C_8$ and $C_9$ respectively. For a hydrostatically supported ship, such as a conventional monohull, the displaced hull form volume ($DP_{6.2}$) supports the total weight ($FR_{6.2}$). Therefore, the submerged shape of the hull form is considered carefully during DP selection. In order to achieve the necessary speed, the total resistance must be considered and minimized ($FR_{6.3}$) over the expected operating speed range. To that end, the hull form characteristics represented by the naval architecture coefficients of

form ($DP_{6.3}$) are evaluated. Coefficients of form include the prismatic coefficient ($C_P$) and the waterplane area coefficient ($C_W$). But, as indicated in the design equation, both $DP_{6.1}$ and $DP_{6.2}$ must also be regarded as resistance contributors.

Since personnel and equipment are enclosed by both the superstructure and the hull, the decomposition of $DP_{6.1}$ is similar to that of $DP_{4.3.2.1.2.2}$. An additional FR defines the hull. The FR/DP pairs and design equations (Equation 3.66) are listed.

| | |
|---|---|
| $FR_{6.1.1}$ = Allow linear placement of equipment | $DP_{6.1.1}$ = Hull extents |
| $FR_{6.1.2}$ = Allow vertical clearance for personnel and equipment | $DP_{6.1.2}$ = Number of decks and average deck height |
| $FR_{6.1.3}$ = Ensure watertight integrity | $DP_{6.1.3}$ = Hull structure |

$$\begin{Bmatrix} FR_{6.1.1} \\ FR_{6.1.2} \\ FR_{6.1.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ x & O & X \end{bmatrix} \begin{Bmatrix} DP_{6.1.1} \\ DP_{6.1.2} \\ DP_{6.1.3} \end{Bmatrix} \tag{3.66}$$

The overall linear dimensions of the ship must be determined in order allow linear placement of all equipment ($FR_{6.1.1}$). Therefore, the hull extents ($DP_{6.1.1}$), as defined with further decomposition, are specified to begin design of the actual hull. Just as in the deckhouse, several hull decks are required to allow vertical clearance for personnel and equipment ($FR_{6.1.2}$). This FR is satisfied by setting the number of decks vertically spaced in intervals equalling the average deck height ($DP_{6.1.2}$). The hull structure ($DP_{6.1.3}$) ensures watertight integrity ($FR_{6.1.3}$). $DP_{6.1.1}$ somewhat affects $FR_{6.1.3}$ because the need for longitudinal strength is roughly based on ship's length. If the hull is not structurally strong longitudinally, failure occurs allowing water to penetrate the hull structure.

$DP_{6.1.2}$ is a leaf node, but $DP_{6.1.1}$ and $DP_{6.1.3}$ require additional decomposition[3]. The following FR/DP pairs functionally define the decomposition of $DP_{6.1.1}$. The selected DPs are mapped according to the design equations (Equation 3.67). An additional constraint bounds

[3] $DP_{4.3.2.1.2.2.1}$, the deckhouse structure, also requires additional decomposition. But, when using the abbreviated decomposition scheme, further refinement of this DP does not add to the study. Therefore, it is not discussed and is contained only in Appendix B.

the selection of $DP_{6.1.1.2}$ as given below

$FR_{6.1.1.1}$ = Facilitate longitudinal placement — $DP_{6.1.1.1}$ = Length on design waterline (LWL)

$FR_{6.1.1.2}$ = Facilitate transverse placement — $DP_{6.1.1.2}$ = Beam

$$C_{13} = \text{Ship beam must contain machinery box beam}$$

$$\begin{Bmatrix} FR_{6.1.1.1} \\ FR_{6.1.1.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP_{6.1.1.1} \\ DP_{6.1.1.2} \end{Bmatrix} \tag{3.67}$$

The hull extents of length ($DP_{6.1.1.1}$) and beam ($DP_{6.1.1.2}$) facilitate respectively longitudinal ($FR_{6.1.1.1}$) and transverse ($FR_{6.1.1.2}$) placement of systems and equipment. Fitting the required propulsion and electrical generation machinery in the hull is a major design task. Therefore, $C_{13}$ defines the minimum transverse beam allowable to ensure adequate clearance for this machinery. The extent of the spaces containing these large items is called the machinery box.

The hull structure ($DP_{6.1.3}$) contributes significantly to the overall design. Through decomposition, four FRs are identified and satisfied by the selected DPs. The pertinent pairs are listed below followed by the decoupled design equations given in Equation 3.68. Four additional constraints significantly guide the setting of $DP_{6.1.3.2}$.

$FR_{6.1.3.1}$ = Provide access to all spaces without compromising watertight integrity — $DP_{6.1.3.1}$ = Watertight closable openings

$FR_{6.1.3.2}$ = Prevent water from entering over the sides — $DP_{6.1.3.2}$ = Depth at Station 10 ($D_{10}$)

$FR_{6.1.3.3}$ = Prevent water from entering through skin of ship — $DP_{6.1.3.3}$ = Exterior hull construction

$FR_{6.1.3.4}$ = Prevent progressive flooding — $DP_{6.1.3.4}$ = Internal hull partitioning

$$
\begin{aligned}
C_{14} &= D_{10} \text{ must contain machinery box height} \\
C_{15} &= D_{10} \geq N_{DECKS} * H_{DK} \\
C_{16} &= \text{Must satisfy longitudinal strength criteria } (D_{10} \geq \frac{LWL}{15}) \\
C_{17} &= \text{Keep deck edge above water at } 25^{\circ} \text{ heel}
\end{aligned}
$$

$$
\begin{Bmatrix} FR_{6.1.3.1} \\ FR_{6.1.3.2} \\ FR_{6.1.3.3} \\ FR_{6.1.3.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ X & O & X & O \\ X & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{6.1.3.1} \\ DP_{6.1.3.2} \\ DP_{6.1.3.3} \\ DP_{6.1.3.4} \end{Bmatrix} \tag{3.68}
$$

Water can enter and travel through the ship several ways. Since access is required external to the skin of the ship, means of exiting and entering must exist. These means must not compromise the hull's watertight integrity. Additionally, access must also be attained to all spaces within the ship's interior. $FR_{6.1.3.1}$, provide access to all spaces without compromising watertight integrity, states this requirement. The use of watertight closable openings such as doors, hatches, and portholes ($DP_{6.1.3.1}$) satisfies this requirement. Waves hitting the ship and cresting over it cause the potential for water to enter over the sides. Thus, $FR_{6.1.3.2}$, prevent water from entering over the sides. Designing sufficient freeboard provides the necessary structure to satisfy $FR_{6.1.3.2}$. Freeboard is the vertical distance from the waterline to the top of the hull (excluding superstructure). Because the ship must always operate at the DWL ($C_{11}$), the freeboard remains constant and is determined by the depth at station 10 ($DP_{6.1.3.2}$). $D_{10}$ is the vertical distance measured at midship from the keel to the top of the hull (again, excluding superstructure). Several criteria constrain the selection of $D_{10}$.

$FR_{6.1.3.3}$, prevent water from entering through skin of ship, is satisfied by $DP_{6.1.3.3}$, exterior hull construction. If the hull is penetrated, especially below the waterline, the sea will enter. Hull construction of adequate strength and durability minimize this possibility. $DP_{6.1.3.1}$ also contributes to satisfying $FR_{6.1.3.3}$. If the sea enters the hull, the flooding must be contained in order to prevent spreading throughout the interior of the ship. $FR_{6.1.3.4}$, prevent progressive flooding, is that requirement. Progressive flooding is contained by $DP_{6.1.3.4}$, internal hull partitioning. The concept of using internal hull partitioning is known as compartmentalization.

$DP_{6.1.3.1}$ also contributes to satisfying $FR_{6.1.3.4}$.

To arrive at the final evaluated $FR_{6.1}$ sub-branch, $DP_{6.1.3.4}$ is decomposed as follows. The FR/DP sets are given below along with the design equations (Equation 3.69).

$FR_{6.1.3.4.1}$ = Prevent longitudinal progressive flooding

$FR_{6.1.3.4.2}$ = Prevent transverse progressive flooding

$DP_{6.1.3.4.1}$ = Longitudinal watertight bulkheads

$DP_{6.1.3.4.2}$ = Transverse watertight bulkheads

$$\left\{ \begin{array}{c} FR_{6.1.3.4.1} \\ FR_{6.1.3.4.2} \end{array} \right\} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \left\{ \begin{array}{c} DP_{6.1.3.4.1} \\ DP_{6.1.3.4.2} \end{array} \right\} \tag{3.69}$$

The prevention of progressive flooding in the longitudinal and transverse directions must be accomplished. $FR_{6.1.3.4.1}$, prevent longitudinal progressive flooding, is fulfilled by $DP_{6.1.3.4.1}$, longitudinal watertight bulkheads. $FR_{6.1.3.4.2}$, prevent transverse progressive flooding, is fulfilled by $DP_{6.1.3.4.2}$, transverse watertight bulkheads.

Additional decomposition of $DP_{6.2}$, the displaced hull form volume, is required. The child FR/DP pairs are listed below. Each of these FRs is fulfilled as shown in the design equations (Equation 3.70).

$FR_{6.2.1}$ = Remain at constant displacement

$FR_{6.2.2}$ = Maintain even transverse orientation (0° list)

$FR_{6.2.3}$ = Maintain even longitudinal orientation (0 trim)

$DP_{6.2.1}$ = Consistent loading philosophy

$DP_{6.2.2}$ = Centerline and symmetric (port/stbd) liquid tanks

$DP_{6.2.3}$ = Longitudinal evenly spaced liquid tanks

$$\left\{ \begin{array}{c} FR_{6.2.1} \\ FR_{6.2.2} \\ FR_{6.2.3} \end{array} \right\} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & O & X \end{bmatrix} \left\{ \begin{array}{c} DP_{6.2.1} \\ DP_{6.2.2} \\ DP_{6.2.3} \end{array} \right\} \tag{3.70}$$

$FR_{6.2.1}$ compliments $C_{10}$, always operate at the DWL. $DP_{6.2.1}$, consistent loading philosophy, satisfies the functional requirement and provides a way to comply with the constraint.

By designing only centerline and port/starboard symmetric liquid tanks ($DP_{6.2.2}$), the ship's transverse orientation is controllable and a 0° list is always attainable ($FR_{6.2.2}$). Similarly, by designing evenly spaced liquid storage tanks over the entire ship length ($DP_{6.2.3}$), the longitudinal orientation is also controllable allowing 0 trim at all times ($FR_{6.2.3}$). Placement of all items contained in the designated loading must be considered to maintain an even transverse and longitudinal keel. Thus, $DP_{6.2.1}$ contributes to both $DP_{6.2.2}$ and $DP_{6.2.3}$. All first child level DPs on the $FR_{6.1}$ sub-branch are leaf nodes except $DP_{6.2.1}$.

The decomposition of $DP_{6.2.1}$ consists of the two FR/DP pairs listed below. The design equations (Equation 3.71) show an uncoupled mapping between the functional and physical domains.

| | |
|---|---|
| $FR_{6.2.1.1}$ = Allow for weight additions and removals (other than burning fuel) | $DP_{6.2.1.1}$ = Ballast system |
| $FR_{6.2.1.2}$ = Allow for weight removal caused by fuel burning | $DP_{6.2.1.2}$ = Compensated fuel system |

$$\begin{Bmatrix} FR_{6.2.1.1} \\ FR_{6.2.1.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP_{6.2.1.1} \\ DP_{6.2.1.2} \end{Bmatrix} \tag{3.71}$$

A consistent loading philosophy ($DP_{6.2.1}$) implies that the weight of the variable load will remain constant while underway. Therefore, ways to allow for weight additions and removals ($FR_{6.2.1.1}$) and weight removal caused by fuel burning ($FR_{6.2.1.2}$) must be designed. These requirements are satisfied respectively by the ballast system ($DP_{6.2.1.1}$) and a compensated fuel system ($DP_{6.2.1.2}$). A compensated fuel system automatically replaces the volume of consumed fuel with an equal volume of salt water.

$DP_{6.3}$, hull form characteristics, requires further decomposition. The three child level FR/DP pairs define the leaf nodes for this sub-branch. Mapping between the functional and physical domains is accomplished via Equation 3.72, the design equations.

| | |
|---|---|
| $FR_{6.3.1}$ = Minimize residuary resistance | $DP_{6.3.1}$ = Hull form factors |
| $FR_{6.3.2}$ = Minimize friction resistance | $DP_{6.3.2}$ = Submerged hull / water interaction |

$FR_{6.3.3}$ = Minimize air resistance $DP_{6.3.3}$ = Frontal area

$$\left\{\begin{array}{c} FR_{6.3.1} \\ FR_{6.3.2} \\ FR_{6.3.3} \end{array}\right\} = \left[\begin{array}{ccc} X & O & O \\ O & X & O \\ O & O & X \end{array}\right] \left\{\begin{array}{c} DP_{6.3.1} \\ DP_{6.3.2} \\ DP_{6.3.3} \end{array}\right\} \tag{3.72}$$

$FR_{6.3.1}$, $FR_{6.3.2}$, and $FR_{6.3.3}$ address the three main types of drag affecting the hull. Appendage drag from propellers, sonar domes, and skegs also contribute to the ship's resistance. If used, previously made design decisions already placed these appendages on the ship. Therefore, the effect cannot be altered at this stage. $DP_{6.3.1}$, the hull form factors, $DP_{6.3.2}$, the submerged hull / water interaction, and $DP_{6.3.3}$, the frontal area, are the factors which may be altered to achieve minimum resistance. Acceptable resistance enables the ship to reach the designated sustained speed.

$DP_{6.3.3}$ is a leaf-level node. The two remaining third tier DPs require further decomposition. $DP_{6.3.1}$ decomposes into the succeeding two additional FR/DP sets. Functional mapping is given in the design equations (Equation 3.73).

$FR_{6.3.1.1}$ = Minimize resistance caused by hull "fullness" $DP_{6.3.1.1}$ = Maximum section coefficient (Cx)

$FR_{6.3.1.2}$ = Minimize resistance caused by underwater hull volume $DP_{6.3.1.2}$ = Volumetric coefficient ($C_v$)

$$\left\{\begin{array}{c} FR_{6.3.1.1} \\ FR_{6.3.1.2} \end{array}\right\} = \left[\begin{array}{cc} X & O \\ X & X \end{array}\right] \left\{\begin{array}{c} DP_{6.3.1.1} \\ DP_{6.3.1.2} \end{array}\right\} \tag{3.73}$$

The hull form factors, which define the hull shape, cause residuary resistance. To achieve the desired sustained speed this type of drag must be minimized. Specifically, the following types of hull shape resistance must be minimized, resistance caused by hull "fullness" ($FR_{6.3.1.1}$) and resistance caused by underwater hull volume ($FR_{6.3.1.2}$). The form factors responsible for these two drag contributions are respectively the maximum section coefficient ($C_X$) ($DP_{6.3.1.1}$), in conjunction with the previously set prismatic coefficient, and the volumetric coefficient $(C_v)(DP_{6.3.1.2})$. $DP_{6.3.1.1}$ affects $FR_{6.3.1.2}$ because $C_X$ affects the underwater hull

volume.

$DP_{6.3.2}$, submerged hull / water interaction, requires further decomposition. The two child level FR/DP pairs define the leaf nodes for this sub-branch. Mapping between the functional and physical domains is accomplished via Equation 3.74, the design equations

$FR_{6.3.2.1}$ = Produce viscous resistance forces (drag)

$DP_{6.3.2.1}$ = Relative motion between submerged hull and water

$FR_{6.3.2.2}$ = Produce contact between hull and water

$DP_{6.3.2.2}$ = Wetted surface area

$$\begin{Bmatrix} FR_{6.3.2.1} \\ FR_{6.3.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP_{6.3.2.1} \\ DP_{6.3.2.2} \end{Bmatrix} \tag{3.74}$$

Without $DP_{6.3.2.1}$, relative motion between submerged hull and water, the phenomenon of drag does not exist. Therefore, to produce viscous resistance forces ($FR_{6.3.2.1}$), the ship must be moving in the water. Or, the ship could be stationery while the water moves. For simplicity, it is assumed that all relative motion is created by the ship moving within the designated operating speed range. The amount of viscous, or friction, resistance encountered is a function of $DP_{6.3.2.2}$, the wetted surface area. This surface area actually produces contact between the hull and water ($FR_{6.3.2.2}$).

## 3.5 Conceptual Design Closure

Hierarchial definition of the entire concept level naval surface combatant beginning with the six highest level functional requirements and growing to all respective leaf levels is complete. This design hierarchy comprised of 874 FR/DP pairs mapped from the functional domain to the physical domain with 73 design matrices is based on one naval architect's perspective. Alternate hierarchies undoubtedly exist based on the differing perspectives and experience within the naval ship design community. Any conceivable design hierarchy must be evaluated for functional dependencies. Whenever possible and physically realizable, these dependencies require eliminating via the introduction of alternate design parameters, or alternate functional definition. In all cases, physical couplings must be controlled by proper satisfaction of functional

requirements with due regard to satisfaction of applicable constraints.

Following the proposed ship design methodology, conceptual design equations are formulated such that the entire decomposed design hierarchy satisfies the Independence Axiom. Design constraints limiting the selection of design parameters are interjected when necessary. These constraints apply to the respective node, as well as to all subsequent child level nodes.

The next step in the design process is to replace all appropriate conceptual design equations with engineering expressions. That is, when appropriate, each conceptual $X$ is replaced with an equation, or group of defining expressions, linking the functional requirement to the contributing design parameters. As the design physically materializes, adherence to the constraints becomes increasingly important. Upon conclusion of this process, the proposed design is quantified as a physically feasible concept level naval surface combatant.

# Chapter 4

# Design Quantification

With conceptual formulation of the design equations and definition of a strategy limiting the level of necessary design detail outlined, the process of design quantification begins. The true test of the proposed design methodology occurs with this evolution. Careful evaluation of the design parameters used to satisfy each functional requirement reveals couplings. By applying axiomatic design theory, these couplings are controlled by fulfilling the functions in a scientifically based sequential progression. Decomposing to increasing levels of detail, and once again adhering the Independence Axiom, completes the entire conceptual ($X$ and $O$ design matrix elements) axiomatic design. Physical interactions between parameters, encountered when fulfilling all functions, have only been deduced conceptually through the application of logic. This portion of the analysis determines if the applied logic is in fact reasonable and correct.

## 4.1 Approach

The goal of design quantification is the creation of an entire balanced warship defined by the functions it must fulfill. The detailed design of individual systems is not pursued. Therefore, the design adheres to the "macro" perspective of ship design. This design formulation assumes that mature systems and components are available for implementation as DPs. These elements have been designed and tested by various engineers, then provided to the naval architect for inclusion in to the overall ship design. Therefore, decomposition stops at the level before

detailed system design begins. The naval architect's task is twofold, the integration of all systems into a feasible ship and the design of a hull containing the numerous required systems. Of course, if a legacy system is neither available, nor desired, axiomatic design facilitates the development of completely new technologies.

To manifest the satisfaction of all necessary FRs, the DPs must be physically transformed into a realizable concept ship obeying the laws of physics. The MIT XIII-A Ship Synthesis Model (math model) currently accomplishes this task sufficiently for the purposes of this study. Because this model accepts the "design spiral" mentality, it relies on an iterative, more often than not, *ad hoc* approach. When using this model, the designer selects gross hull parameters (DPs), and verifies if a converged design results. As stated in Section 1.4, this model synthesizes a ship with regards to weight, volume, area, electrical power, propulsive power, and transverse intact stability. If convergence in all aspects is not attained, the designer modifies the previous DP selections and once again evaluates the design. This process often repeats several times until a balanced ship exists. Since the math model does not necessitate a strict order for parameter definition, the overall ship effect of modifying a particular DP may not truly be understood. In fact, many important DPs are treated as global variables which are recognized throughout the whole model, but defined at the end of the model in global fashion. That is, some parameters set previously are effected by the modifying of these values, thereby simultaneously influencing many aspects of the ship through often transparent feedforward couplings.

Speculation deems that an approach limiting the haphazard nature of DP selection improves the utility of the math model as a ship synthesis tool. Additional logic also concludes this method should aim to disregard the acceptance of conforming exclusively to an iteration based methodology. Since the math model already demonstrates the ability to physically manifest a conceptual ship design, the task becomes to develop a more logical, repeatable approach to parameter definition. To accomplish this task, the math model structure is studied alongside the design hierarchy of the conceptual design equations. This reveals that many of the math model equations and direct inputs map directly into the axiomatic design framework as either DPs, design equation elements (conceptual $X$'s), or a combination of both. Thus, advancing the math model through axiomatic design theory is pursued.

## 4.2 Model Development and Usage

Since a concept design with the same level of fidelity as the math model output is desired, only similar systems are defined in this restructuring process. The math model level of fidelity implies a converged design regarding the stated six aspects. System definition occurs using existing math model equations, some in modified form, and direct input values. The complete axiomatic design hierarchy contains significantly more functions requiring satisfaction than the math model contains equations. And, some math model equations represent cumulative effects of many design decisions within a single hierarchy branch as the outright fulfillment of a function without additional decomposition. Therefore, not all conceived FRs are directly satisfied by interjecting math model elements. On the other hand, some of the math model inputs actually manifest the cumulative effect of many design decisions. In these cases, control and selection of all pertinent parameters must always be maintained and tractable.

As stated, to satisfy the design equations at each necessary level of the hierarchy, math model elements are used. In some instances, this represents the assigning of a numerical value for the pertinent DP. In other instances, satisfying the FR requires the insertion of a physical component or system. In this case, such DPs are manifested by one, or more, of the following physical quantities: weight, relative vertical center of gravity, volume, area, and electrical power consumption. Assigning the appropriate math model expressions by following the sequence developed during the generation of conceptual design equations decouples the concept level ship quantification process.

The ship synthesis tool resulting from using axiomatic design techniques to remove the *ad hoc* methodology is further referred to as the MIT XIII-A Functional Ship Synthesis Model, or simply the functional math model. Appendix C contains the functional math model. This model follows the conceptual design equation order for satisfying FRs. Specifically, all six FRs are satisfied in sufficient detail to produce a ship with a math model level of fidelity. Each respective DP is set until the applicable pseudo leaf level, then the next branch in the upper level decomposition is addressed. The development and usage of this model provides valuable insight into the physical couplings associated with functional fulfillment.

Detailed explanation of all functional math model equations is not undertaken because most equations are directly taken from the currently accepted math model, which were pre-

viously adopted from various U.S. Navy ship design studies. Explanation ensues to explain the instances where significant deviation from these acceptable equations exists. Significant deviations are neither desired, nor anticipated unless unwanted couplings cannot be broken by the axiomatic design determined reordering of DP assignment. Primarily, systematically reordering the assignment of DPs based on functional interactions results in the elimination of feedback couplings. And, by replacing some equations with directly input DP values, the designer maintains more control of the overall design.

Physical representation of DPs occurs at all levels within the design hierarchy. This is different from most axiomatic design applications. Current practice applies engineering expressions to manifest DPs only at the leaf level, upper level DPs are usually only conceptually envisioned and designed. This approach does not provide sufficient detail for ship design because many decomposed DPs physically build on the higher level systems. For example, the fuel system providing fuel to the propulsion engines directly relies on the selection of propulsion engines. Both DPs require physical placement on the ship. Therefore, DPs are defined physically in sufficient detail to fulfill functions at all levels in the decomposition.

To initiate the design process, certain customer attributes (CAs), specifically, sustained speed, endurance speed, endurance range, and stores period, require mapping into the functional domain. For a design to be acceptable, these CAs, contained in the respective Operational Requirements Doctrine (ORD) and given to the appropriate design team, must be satisfied. Certain design constraints are used to assist the verification effort. The designated manning is additionally required to initiate the design process. The ship's complement may also be given in the ORD or, more appropriately, the functional allocation process may be used to determine the appropriate number of personnel required to fulfill all shipboard functions. Functional allocation occurs prior to commencing design by evaluating the lower level tiers in the decomposition. Therefore, all conceptual design equations must be formulated prior to commencing design quantification A proposed functional allocation procedure is discussed in detail in Chapter 5.

After the requisite CAs are defined, the process of fulfilling functional requirements begins. One unique feature incorporated into the functional math model not found in the original math model is an interactive way to account for the characteristics of some of the direct input physical system DPs, specifically the DPs associated with weapons systems. Because of functional

definitions, these specific DPs span fulfillment of $FR_2$ through $FR_6$. By accessing an imbedded Microsoft Excel spreadsheet, the designer inputs DPs with associated characteristics, weight, area, etc., during the design process when prompted. This "component" tabulates the cumulative characteristic values for input into the model when required. Appendix C also contains the spreadsheet output of a fully utilized Excel component. In order to utilize this feature, the designer must possess a database of weapons systems and characteristics, such as the payload and adjustments tables used in ASSET modelling.

All required inputs are highlighted to ensure the designer understands setting of the DP value, or accepting the default DP value, is necessary. In all, the functional math model requires 114 inputs. Portions of these inputs which are added to the Excel component require multiple information for complete definition. Of course, as FRs are either increased or decreased the number of DPs varies. The salient point of this model is that DPs are specified in a logical sequence resulting in no feedback couplings. Because inputs in the form of DPs fulfilling FRs are always introduced in the same sequential order, the *ad hoc* approach vanishes.

After all math model equations are accounted for through assignment of the appropriate math model element, an analysis to determine if physical feedback couplings exist as a result of the parameters used in the equations. In situations where this is true, alternate methods of defining the DP are required. Surprisingly, after implementing the axiomatic design derived sequence, few of these situations arise. But, as a result of using some regression based parametrics requiring the specification of gross hull parameters and displaced volume, some exist nonetheless. Reference [16] includes examples of these regression type relationships. Therefore, alternate means for parameter definition are implemented.

The primary means of eliminating couplings resulting from the use of parametrics at an inappropriate stage of the design process is having the designer directly input the value for the designated DP. Of particular importance is the designer's selecting of the length ($LWL$) and the beam ($B$) on the waterline. Other examples include specifying the propeller shaft length, bridge area, electrical power requirement for the steering and underway replenishment systems, weight of the mast and internal communications system, and volume of the waste oil and fuel system tanks. These input values rely on the designer's experience, or access of a database containing existing systems. In either case, the designer completely controls the design of the

system.

The removal of another feedback coupling exists by relying on the previous design decisions. The original math model determines the beam of the machinery box, the spaces containing the ship's propulsion engines, by assuming the ship's beam. Since applying the improved ordering leads to the specification of the ship's beam subsequent to specification of the machinery box beam, a potential feedback coupling results. Therefore, to eliminate this problem, specification of the machinery box beam is based on the selected propulsion engine's width and quantity. A constraint is then placed on the subsequent setting of the ship's beam stating the machinery box beam must be enclosed.

Another example highlighting the use of previous design decisions to remove feedback coupling uses a modified parametric. Several DPs specifying electrical power requirements are calculated as a power requirement per volume. This volume being the product of the overall ship dimensions ($LWL$, $B$, and draft($T$)). Once again, these overall dimensions are defined subsequent to requiring the electrical power DPs. Therefore, a means to estimate the volume determined by overall gross ship dimensions is required. Based on the already determined required deckhouse area, the following parametric approximating the product of the gross hull dimensions is formulated and incorporated to satisfy the respective DP definitions: $(4 * H_{DK} * A_{DR})$. A similar parametric is devised to determine the auxiliary system operating fluid weight which initially requires the full load volume, $V_{FL}$. Once more a feedback coupling is eliminated by approximating $V_{FL}$ with $(6 * H_{DK} * A_{DR})$.

Calculation of the hull structural weight requires the average hull height above the keel. The average hull deck height ($D_{AV}$) is currently used as a simplifying parameter to build up to the value for average hull height. The direct input of the depth at Station 10 ($D_{10}$), the midships location, replaces $D_{AV}$.

The incorporation of constraints assists the designer in selecting logical DPs. Therefore, constraints are an integral part of the design process. All the constraints addressed in the conceptual axiomatic design formulation play a direct role in the functional math model. In all, 17 constraints are used. Constraint evaluation becomes vital to ensure a physically realizable ship results from the selection of all design parameters. Additionally, constraint evaluation verifies the resulting design meets the customer's expectations, i.e., satisfies the CAs. If a

constraint is not satisfied, the designer must re-evaluate the contributing DPs and modify as necessary to ensure compliance.

The outlined process marries axiomatic design theory with the MIT XIII-A Ship Synthesis Model. Once a converged concept level design is achieved, the total program ownership cost is calculated using the identical weight based cost model used by the original synthesis model. Total ownership cost sums the initial acquisition cost with the life cycle operating cost. Figure 4-1 shows the design process followed by the functional math model.

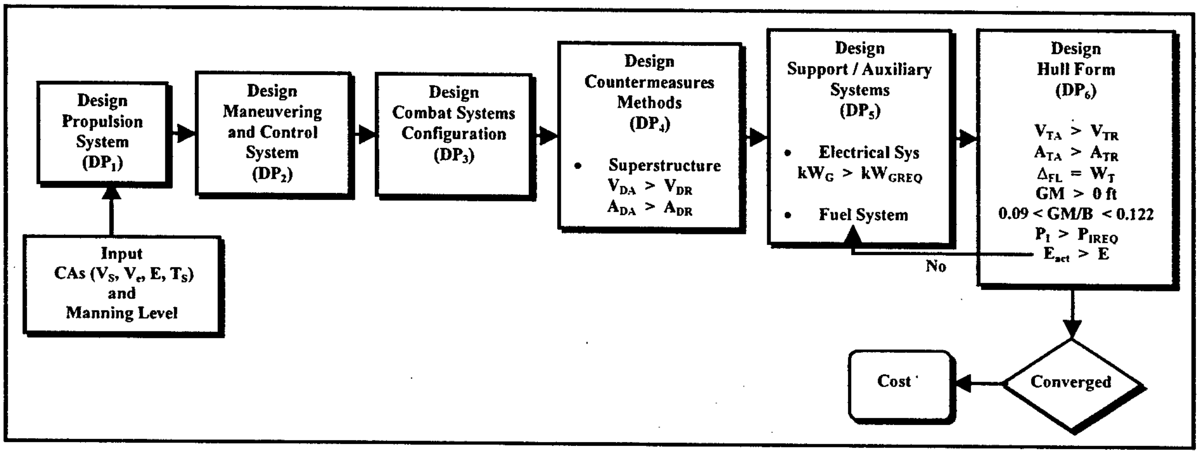



Figure 4-1: Functional Math Model Process

## 4.3 Verification

Upon conclusion of all necessary alterations, the accuracy of the resulting MIT XIII-A Functional Ship Synthesis Model must be determined. For this test, a fictitious ship called the DD13A is first synthesized using the original math model, and then synthesized using the functional math model. This ship represents a robust evaluation platform because it fulfills a broad range of functions, such as neutralizing enemy air, surface, and surface threats. Therefore the DD13A possesses a wide array of capabilities (DPs).

The ships resulting upon closure of these two evolutions are compared to ascertain the level of agreement. Since ships designed using the math model are generally accepted as feasible, and this model evolved into the functional math model, the math model balanced ship becomes

the baseline for comparison. Some differences are expected, but the overall designs should not deviate significantly. The ship balanced with the Appendix A math model is the baseline DD13A. The ship balanced with the Appendix C functional math model is the DD13A version requiring verification, the 'variant'.

The test ship is modelled using the same inputs as the baseline with the following exceptions. Certain parameters calculated using regression analysis in the original math model are directly input DPs in the functional math model following the reasoning stated above. In these instances, the regression based DP value is not extracted from the baseline for input into the test ship. But rather, a "database" of existing systems is used to extract the necessary parameter values. In actuality, the database is the output from an ASSET synthesized DDG51 Flight I destroyer.

When the results at certain stages in the functional design process lead the designer to select divergent DPs, the divergent results are input. To do otherwise unnecessarily biases the design to more closely resemble the baseline. Logical setting of DPs is followed to obtain a true representation of the results produced by the test model, thereby increasing the usefulness of this analysis, although, two notable exceptions to this rule exist as follows. Because the designer has the option to design a larger than required deckhouse, this practice is mimicked for the test ship. Not doing so significantly, and unnecessarily, causes design divergence. The test design also uses the same $D_{10}$ as the baseline which is legitimate since no constraints are violated.

The ships have a complement of 150 personnel, 15 officers and 135 enlisted crewmembers, determined solely by the ORD. Functional allocation of tasks was not conducted to ascertain this manning level. The weapons loadout is contained in both Appendix A (grouped according to the U.S. Navy ship work breakdown structure (SWBS)) and Appendix C (grouped by function). Four typical CAs initiate the design process as follows.

$$\begin{aligned}
\text{Sustained Speed } (V_S) &= 28 \text{ knots} \\
\text{Endurance Speed } (V_e) &= 20 \text{ knots} \\
\text{EnduranceRange } (E) &= 7,500 \text{ nm} \\
\text{Stores Period } (T_S) &= 45 \text{ days}
\end{aligned}$$

Upon reaching closure to the synthesizing process, both variants of the DD13A utilize four General Electric (GE) LM2500-21 marine gas turbine engines for propulsion. Each LM2500 outputs 22,750 hp. Accounting for the various inefficiencies in the propulsion system, each ship has 88,270 hp installed for propulsion. Also, producing similar electrical load requirements, each variant utilizes identical prime movers to fulfill electrical generation needs. Specifically, three Allison DDA 501-k34's supplying 3,000 kW of power each. Thus, the electrical generation capability of each variant is 9,000 kW.

A summary of the two variants is listed below highlighting comparison of the important ship characteristics.

| | Math Model Baseline | Functional Math Model Variant | % Difference |
|---|---|---|---|
| $\Delta_{FL}$ | 7,935 lton | 7,457 lton | −6.0 |
| $LW$ | 501.3 ft | 501 ft | – |
| $B$ | 53.7 ft | 54 ft | 0.6 |
| $T$ | 19.9 ft | 18.6 ft | −6.5 |
| $D_{10}$ | 37.0 ft | 37.0 ft | – |
| $C_P$ | 0.61 | 0.61 | – |
| $C_X$ | 0.85 | 0.85 | – |
| $V_{TA}$ | $563,794$ ft$^3$ | $542,577$ ft$^3$ | −3.8 |
| $A_{TA}$ | $62,644$ ft$^2$ | $60,286$ ft$^2$ | −3.8 |
| Req'd Propulsion Power | 83,960 hp | 86,949 hp | −1.7 |
| Req'd Electrical Power | 8,303 kW | 8,514 kW | 2.5 |

## 4.4 Evaluation of Results

The functional math model synthesizes the DD13A baseline as a variant with similar characteristics. All analyzed parameters fall within 6.5% of each respective baseline value. Therefore, the functional math model is considered accurate to the math model level of detail for synthesizing concept level ship design. The major reasons causing differences are understood and outlined next.

Because of the constraint set on the ship's beam, the designer is not able to set the variant

beam equal to the baseline beam. An additional design constraint causes the designer to set the beam at 54 ft, or wider, to contain the machinery box as discussed above. The lighter full load displacement, $\Delta_{FL}$, less available volume and area, and larger required electrical power result from using direct input DP values and the mentioned modified parametrics vice the original math model regression based parametrics. The variant ship also has less volume and area because the functional math model matches these values exactly. The original math model requires iteration to achieve these balances. As a result, the math model baseline DD13A actually has 21,217 ft$^3$ extra volume and 2,358 ft$^2$ extra area.

The required propulsion power of the variant DD13A exceeds the baseline's power requirement because of differences in the way each model determines residuary resistance. Residuary resistance is determined using the results of the Taylor Standard Series (TSS) model testing data [10] augmented with a worm curve factor (WCF). The WCF accounts for differences in resistance between the evaluated hull form and the standard series hull forms. Two different WCF are incorporated into each math model. The original math model requires the direct input of data from a non-specific worm curve. On the other hand, the functional math model automates the worm curve calculation process by using a more standard and conservative WCF resulting in higher resistance predictions.

The ship's draft is directly related to the displaced hull form volume, determined by the full load weight according to Archimedes' Principle, the extreme hull dimensions, and the hull shape factors. As seen in Equation 4.1, as the full load volume decreases and the beam increases, the draft must decrease, and this results in the reduction of the variant draft.

$$T = \frac{V_{FL}}{C_P * C_X * LWL * B} \tag{4.1}$$

The metacentric height to beam ratio is a result of all previous design decisions. The metacentric height results from the displaced hull form geometry and the vertical placement of weights on the ship. The variant has a higher metacenter because of the reduced displaced volume, and therefore reduced weight. With each ship having comparable beams, the increased metacentric height causes a larger $GM/B$ ratio. Both ships sufficiently meet the transverse

dynamic stability criteria, the variant being a stiffer ship.

## 4.5 Summary

The functional math model requires the definition of all shipboard systems before attempting design of the hull form. Although a monohull is demonstrated, this ship synthesis tool supports the design of advanced hull forms as well. Of course, modifications and additions to the model are required to facilitate this. The primary difference is in the resistance and stability 'modules.' However, since these calculations are functionally independent, such computational modules could be coded and inserted directly into the functional math model. A hull, whether it be a monohull, a catamaran, or any other hull form, is conceptually designed to enclose the previously designed systems. In other words, the designer develops the systems first, and then "wraps" the hull around these systems which are placed in the vertical plane to determine transverse intact stability.

Satisfaction of first five FRs occurs relatively easy. There is only one exclusive constraint ($C_7$), two sub-constraints ($C_{8.1}$ and $C_{9.1}$), and a portion of three other constraints ($C_6$, $C_{10}$, and $C_{12}$) requiring attention while designing the DPs to fulfill the first five FRs. Additionally, the two overarching constraints regarding cost ($C_1$ and $C_2$) must always be considered during this process. The numerous FRs the hull fulfills poses a challenging design problem. Specifically, 16 of the 17 design constraints exclusively, or partially, affect hull form design. Particularly, the constraints regarding the enclosure of all required systems and personnel, resistance characteristics and powering, and stability require close attention. These inherent couplings are the major challenges of naval architecture.

### 4.5.1 Improvements to Ship Design Process

Applying axiomatic design theory to the concept level ship design process results in significantly more designer control by completely eliminating the *ad hoc* assigning of DPs and minimizing the need to modify functionally satisfactory DPs once set. Between the upper level FRs, only one possibility for DP reassignment exists. This reassignment is not entirely necessary, but actually more convenient. During satisfaction of $FR_6$, two potential sources for DP redefining

exist due the inherent couplings and physics. Constraint evaluation guides the designer to select appropriate DPs at all levels of decomposition. Even if a given constraint is not met, the designer realizes the DPs causing non-compliance that require modification to resolve the conflict. Constraint satisfaction at strategic points in the design process bounds the selection of certain crucial DPs, therefore keeping design realistic.

The following lists some of the features of the MIT XIII-A Functional Ship Synthesis Model which lead to an overall improved concept level design process.

1. FRs are listed in the proper order as determined by applying the Independence Axiom, thereby removing the *ad hoc* assigning of DPs.

2. Designer is in more control of the design at all stages. All required DPs are highlighted for designer input. The designer is provided minimum required values for pertinent parameters, but may opt to exceed the minimum if required to comply with the design strategy. For example, the deckhouse size may be increased and hull size decreased provided that both total volume and total area are equal to or greater than the required values.

3. Re-assignment of DPs is minimized by listing constraint evaluations at strategic points in the design progression.

4. A large number of regression based parametrics requiring gross monohull parameters ($V_{FL}$, $L$, $B$, $T$) and total ship weight are removed from the model. Equations previously requiring these inputs are replaced to reflect complete design decisions, or are replaced with directly input values.

5. Designs are automatically balanced with regards to area, volume, and weight. Additionally, all electrical loads are determined prior to designing the electrical system, allowing immediate FR fulfillment.

6. An interactive Excel component automatically tabulates the characteristics of physical systems used as DPs in order to determine cumulative factors affecting subsequent DP selection. This component also ensures the accurate vertical placement of these systems

by seamlessly updating all respective vertical centers of gravity as datums ($D_0$, $D_{10}$, and $D_{20}$) are set.

7. Hull resistance calculations are improved by including an automated method to deduce the worm curve factor.

8. Aerodynamic resistance values are more realistic because both hull and deckhouse parameters are used to determine the total exposed frontal area.

9. The functional math model is suited to synthesize ships with non-conventional, advanced hull forms. To achieve this diversity, a means to predict specific hull type resistance, and a way to accurately model hull volume and stability are required.

10. The functional math model is also suited for use with a product data manager (PDM). This is demonstrated by defining payload DPs using the interactive Excel component. Similar spreadsheets are envisioned for the model once a database of potential DPs, including all required specifications, is established. The ultimate goal involves linking a computer aided design (CAD) package to its associated PDM to allow visualization of the systems. As the designer sees the emerging design, an appreciation for systems placement and hull limitations results. The integration of a CAD/PDM to computer-aided engineering (CAE), computer aided manufacturing (CAM), and enterprise resource planning (ERP) is also possible.

### 4.5.2 Limitations of the Functional Math Model

As eluded to above, the physics of hull design does not allow for a "one pass" design solution at all times. Ideally, the designer specifies every major hull parameter. But, the design must be physically realizable for quantification occur. As shown in Equation 4.1, interrelationships exist between the important naval architecture parameters. Therefore, at the very least, one of the six parameters must be the result of specifying the other five parameters. To remain consistent with Archimedes' Principle, draft is the dependent parameter.

When decomposed, the hull form ($DP_6$) satisfies, or affects, the functions unique to ship design. Phenomena associated with ships operating on the surface of the water ($FR_6$) create

inherent couplings that cannot be disregarded through innovative thought and the application of clever assumptions. Specifically, there is always difficulty in minimizing total friction ($FR_{6.3}$), while simultaneously enclosing personnel and equipment ($FR_{6.1}$) and ensuring stable equilibrium ($C_4$ and $C_5$). Application of axiomatic design techniques allows the designer to control these couplings, however all feedback couplings are not completely eliminated. Adherence to both the requisite constraints, interjected at distinct points in the design process, and the design progression dictated by the design equations minimizes the need to alter set valued DPs.

The following lists some of the limitations of the MIT XIII-A Functional Ship Synthesis Model which are not necessarily insurmountable, but require further attention and/or investigation. Not coincidently, most of these limitations result from the resistance and powering interaction common to ship design.

1. The designer determines residuary hull resistance by accessing traditional resistance data pertaining to the TSS. This data is contained in a comprehensive set of graphs [10]. Because this set is so comprehensive, automating the data extraction process poses difficulties. Therefore, manual extraction and entering of resistance coefficients is necessary. Failure to update the pertinent values, when necessary, results in inaccurate hull resistance predictions. Automated resistance computational modules do exist in current ship design tools, such as ASSET.

2. The TSS data is catalogued according to several ratios and non-dimensionalized coefficients derived from the characteristic ship parameters. Each series hull is designated by the beam to draft ratio ($B/T$) and prismatic coefficient ($C_P$). Further resistance specification relies upon the volumetric coefficient ($V_{FL}/LWL^3$) and the speed to length ratio ($V/\sqrt{LWL}$). All DPs required to access the resistance data, with the exception of $C_P$, are specified prior to accessing the resistance tables. Therefore, if the ship fails to meet the installed propulsion power constraint ($C_6$), adjustment of one or more of the previously set parameters is necessary. Another method of cataloging resistance data more conducive to this design approach may be possible, but seems quite unlikely.

3. The large design margin, accounting for "fouling and sea state," used to determine the

required installed propulsion power makes the resistance and powering balance challenging. Equation 4.2 states 25% more power than actually predicted is required to ensure sufficient propulsion power at the customer designated sustained speed. To bypass this challenge, the designer may choose to select more powerful engines at the onset. But, if this power proves too excessive, the cost constraints ($C_1$ and $C_2$) are violated. Investigation to substantiate reducing the design margin is warranted.

$$P_{IREQ} = 1.25 * P_S \tag{4.2}$$

4. Hull resistance at endurance speed, which is not known until satisfying $FR_6$, must be known prior to sizing fuel storage tanks ($DP_{5.8}$) to ensure adequate fuel storage capacity. Since the design equations do not specify this order, the designer uses previous experience and intuition to estimate the required fuel tankage. To ensure the endurance range is achievable with the estimated tankage, constraint verification of the actual fuel required is added upon completion of $FR_6$ satisfaction. True axiomatic design requires altering the hull to produce a total resistance at endurance speed supporting the previously designed fuel tankage. But, experience proves it much easier to simply increase the fuel tankage, than to completely redesign the hull to satisfy the respective constraint ($C_{12}$). Therefore keeping this feedback coupling is recommended. Although, the designer may also modify the necessary hull parameters to comply with the constraint if desired. By designing $DP_{5.8}$ conservatively, the designer removes the need to redesign.

5. The functional model relies on the U.S. Navy SWBS designations when specifying some DPs. To facilitate a smoother PDM implementation for designating and tracking DPs, a functional based accounting scheme is highly desirable for use with the model. Close coordination amongst various logistics, maintenance, and design activities is required to make this transition.

## 4.6 Design Quantification Closure

The effect of design parameter selection on the total ship is always an area of interest. Selection of all DPs physically impacts the entire ship to some extent. Of course, the effect of some DPs is more apparent than others. The MIT XIII-A Functional Ship Synthesis Model more easily (than the iteration based synthesis model) allows these effects to be determined. Since DP assignment proceeds in an exact predetermined order, changing a DP always affects the same downstream aspects. The designer is aware of this as the design matures with each successive design decision.

One particular concern pertaining to DP selection results because both humans and automated machines are capable of fulfilling certain functional requirements. If a human is designated to preform a specified task, the overall ship is affected. Similarly, if an automated machine replaces the human to perform the same task, the overall ship is again affected, but differently. The functional math model reveals the effect of both decisions to designers involved in concept level design.

This functional allocation decisions must be made at the lowest level of design decomposition. By evaluating these lowest tiers in the hierarchy, manning and automation tradeoffs are made, and the appropriate entries are input into the model to initiate the design process. These decisions influence the design from the onset.

# Chapter 5

# Manning and Automation

An unacceptably large portion of the U.S. Navy's budget is spent on manpower. This reality, coupled with the public's aversion to placing personnel in harm's way, forces a fundamental change in the established shipboard manning policy. To address both these issues, the U.S. Navy intends to reduce the manning on warships. As personnel are removed, most functions traditionally performed by them must still be accomplished in order to maintain the ship's warfighting capability. Automated machines are identified as the means to fulfill these necessary functions. Extending the axiomatic design decomposition provides a method to identify all pertinent shipboard functions, thereby assisting designers determine the logical allocation of tasks between humans and automated machines.

## 5.1 Overview

The U.S. Navy is an organization full of tradition. Replacing personnel with automated machines significantly differs from conventional thought and requires a basic cultural change. Inflated watchstanding requirements fill ship procedural doctrines for the simple stated reason: "That's the way it's always been." This attitude has been prevalent due to years of hard "lessons learned" during warship operations. Operators, especially ship commanding officers, gain an increased comfort factor knowing personnel are 'standing by' to respond to casualty situations. Resistance to change is the greatest obstacle to reducing manning on U.S. Navy vessels [3]. For a majority of the reasons against reducing manning and increasing automated

machinery, there exists an unwillingness to change. With research and development efforts channeled in the proper direction, the transition to reduced manned, increasingly automated ships becomes more feasible. As the enabling technologies mature, and the operational doctrine changes become concrete, trust in the reduced manning strategy should elevate.

A vital concern requiring attention is the proper integration of a reduced crew with automated technologies. Human systems integration (HSI) addresses this concern by studying the interaction between humans and technologies. With regards to naval applications, this specifically emphasizes developing methods of improving system reliability by improving human reliability to maintain the ship's operational capabilities [1]. Some major HSI efforts supporting the reduced manning initiative include:

1. Formulating strategies to ensure the reduced crew is not overtasked with increased maintenance duties

2. Developing maintenance procedures to increase productivity when utilized by a reduced crew

3. Determining the interaction between crewmembers and highly reliable automated systems such that complacency and lack of job satisfaction does not result

4. Devising methods to enhance situational awareness by minimizing human information overload

The human is only one facet of the shipboard system. Designers of automated systems must also confront specific issues to ease the transition process. Specific automated systems affecting ship safety, always under strict scrutiny, require development emphasis. In order to alleviate the uneasiness felt by ship commanders, system designers must develop highly reliable damage control and warfighting systems. Close coordination between system designers and HSI engineers ensures optimum benefit of new technologies.

The cost of automation cannot be neglected. The Navy requires affordable high reliability, redundant technologies. Such technologies are used on ships in the commercial ocean industry. With some modification to ensure 'militarization,' these commercial systems are applicable for implementation on naval vessels. Automated systems are viewed as high initial acquisition cost

items. This is especially true during inception because of the extensive testing and evaluation involved. As technologies mature, initial acquisition costs reduce. Because only periodic overhaul of these systems is required, they do not incur a large operating cost. On the other hand, personnel affect the initial acquisition of a ship because the specified manning level influences the overall ship requirements and characteristics. And, each assigned crewmember continually requires support and wages, resulting in large operating costs.

The cost of manning increases proportionately with the crew size, while the cost of automation decreases proportionately with crew size. The combination of manning and automation that fulfills all mission objectives for the minimum cost is considered the optimum combination as shown in Figure 5-1. Since the Navy strives to responsibly appropriate funds, determining this optimal combination is highly desirable. By using a functional allocation procedure, trade-off studies to determine the most cost effective crew size, coupled with the proper aggregate of automated systems, are possible.

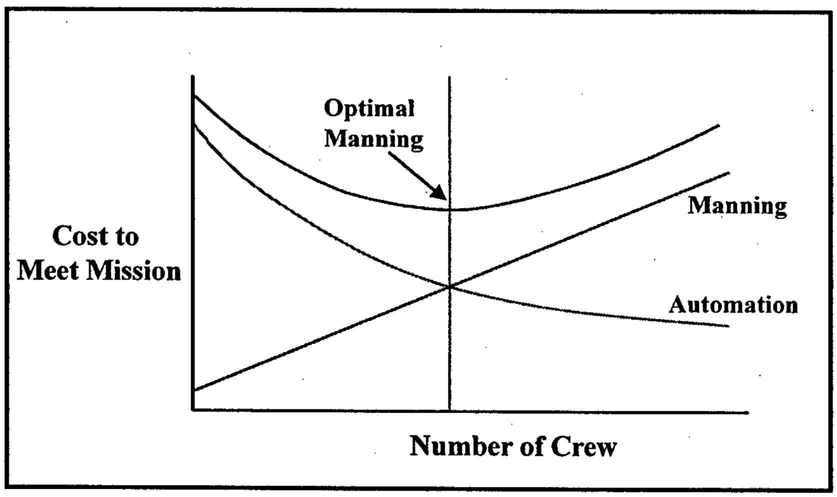



Figure 5-1: The Cost of Manning and Automation to Meet Mission Objectives

## 5.2 Existing Functional Allocation Methodologies

Decisions regarding the overarching manning and automation philosophy must be made at the early stages of concept level design. When designing a new class of naval surface combatants,

these preliminary decisions permeate the entire design process. Because of the rapid advances in computer networking, sensing devices, electrical power processing, etc., decisions based solely on mature physical systems are not prudent. Based on the long time required to design and construct ships and relying only on existing technologies, results in an obsolete ship entering the fleet. Conversely, basing the entire program on the development of certain enabling technologies also poses problems. If the technologies never materialize, significant modifications are required to make the ship feasible.

Current functional allocation practice regarding manning and automation seems to consider the technologies before the functions. Therefore, design occurs in the physical domain prior to occurring in the functional domain. In other words, a new automated system emerges for use aboard ship, and then during implementation, the designers determine its effect on manning. Because all mission scenarios are rarely evaluated, the removal of crewmembers is neither substantiated, nor contradicted. The overall ship impact resulting from the introduction of the automated feature is not really known.

Other functional allocation methodologies consider functions first. One such proposed methodology begins by setting a target manning level, then formulates baseline assumptions regarding operational and maintainability guidelines [8]. As the process advances, operators are queried to review system requirements and establish a functional allocation philosophy. Considering this philosophy, designers allocate functions between humans and automated systems (both mature and conceptual).

The allocation plan is evaluated to determine if the operational requirements and manning goals are met. If operational requirements are not achieved, the systems require redesigning. If the manning goal is not achieved, an evaluation of the entering philosophy ensues. If this evaluation determines the target manning level is valid, system redesign is once again required. If further consideration reveals the philosophy does not support the target manning, the philosophy requires revision. Once both the operational requirements and the manning goals are met, detailed system design commences. This procedure is iterative in nature because a manning goal is set and evaluated for feasibility, rather than determining a feasible manning level.

## 5.3 Proposed Functional Allocation Process

Iterative procedures require time and effort to achieve convergence. Additionally, the iterative nature of the functional allocation process often requires philosophical changes to be accepted by the design team. Thus, a rigorous iteration-free approach to functional allocation appears attractive, especially as the Navy endeavors to reduce crew sizes. Extending the axiomatic design based ship design methodology provides a vehicle to develop such a theoretical functional allocation framework.

### 5.3.1 The Ship as a Large Flexible System

The conditions on and around a ship constantly change. This constant state of flux, caused primarily by shipboard evolutions, casualty situations, and operational scenarios, directly influences the functions a particular ship must perform at any given time. In other words, the time variant states the ship experiences causes the ship's functional requirements to also be time variant. In the AAD framework, complex systems which exhibit this type of time variant behavior are called large flexible systems [19]. For functional allocation purposes, all anticipated states must be analyzed.

At the higher levels in the design hierarchy, the ship is viewed in a state neutral environment. In this broad view, design parameters (systems, subsystems, and components) are incorporated into the design such that all conceivable conditions are taken into account. As the hierarchy grows, the design is defined in greater detail until eventually 'tradeoff nodes' appear at the lower levels. Tradeoff nodes contain the DPs which require additional functional decomposition to support manning and automation decisions. This is the current status of the design hierarchy as developed in Chapter 3. Within each state, further decomposition is only required to account for the additional FRs of each contributing DP.

Most shipboard FRs are satisfied by the same DP regardless of state, based on the original design decisions. And, many DPs only have the ability to fulfill one FR. When the DP is a human being, this is not the case. Possessing cognitive skills, humans are the most adaptive and flexible design parameter available. Humans have the ability to fulfill different FRs as required by the conditions presented in the existing state. The actual FRs fulfilled

by personnel vary from minimal in some states to extensive in other states. Logical reasoning dictates that designers must account for all foreseeable contingencies in all states. Therefore, the crew size for a particular ship is the sum of all personnel needed to function simultaneously to accomplish all tasks within the most demanding readiness condition (state). If automated machines are chosen as the design parameters fulfilling a portion of these functions, the crew size may be reduced.

U.S. Navy ships operate according to the potential threat perceived within the immediate operational environment. As the likelihood and consequences of the perceived threat increase, the ship's readiness posture proportionately increases in preparation for potential confrontations. As the ship's readiness posture increases, a larger number of FRs pertaining to self defense and ship control require satisfaction. The five standard conditions of readiness (COR's) comprise five states for consideration during the functional allocation process. For reference, these COR's with a brief explanation follow in descending order (i.e., Condition I is the most capable posture).

| | |
|---|---|
| Condition I | General Quartrers Wartime Steaming - Battlestations manned, no movement throughout ship |
| Condition II | Relaxed General Quartrers Wartime Steaming - Battlestations manned, limited movement throughout ship |
| Condition III | Increased Readiness Peacetime Steaming - Peacetime watchstations manned augmented with designated tactical watchstations |
| Condition IV | Peacetime Steaming - Peacetime watchstations manned |
| Condition V | Inport - Minimal watchstations manned |

Various shipboard evolutions, both planned and unplanned, cause a change in state. In the case of unplanned damage control evolutions, an instantaneous change in state happens requiring the immediate reconfiguration of DPs. Specifically, rapid response by personnel and/or automated machines is necessary to mitigate adverse effects. Some of the common internally driven states which also bring about unique FRs are listed with a brief description. This list is neither given in any significant order, nor is it all encompassing.

| | |
|---|---|
| Damage Control | General Quarters responding to fires, flooding, etc. |
| Sea and Anchor Detail | Transiting into and out of port |
| Flight Quarters | Launching and recovering aircraft (helicopters) |
| Underway Replenishment | Receiving fuel and/or stores alongside a replenishment vessel |

### 5.3.2 Functional Accountability

The design decomposition developed in Chapter 3 is always the starting point for continuing analysis of each specific state. As terminated, this decomposition defines a physically constructed ship. The ship is then projected into an operational scenario, the given state. Once in the state, additional functional requirements pertaining to the designed systems, subsystems, and components arise. Thus, further decomposition of the affected DPs accounts for these additional requirements. Non-affected DPs do not require further decomposition. Certain functions such as routine administrative, upkeep, and maintenance duties exist regardless of the operational state. Reduced manning initiatives also discuss eliminating a portion, if not all, of these functions. These functions must be accounted for in the design hierarchy if not eliminated.

Accountability of functions affecting potential tradeoffs between humans and automated technologies is crucial to the functional allocation process. Each state requires individual functional formulation and analysis. Multiple extensions are required to account for all operational states. Since the starting point for any analysis is the basic decomposition, new states are incorporated into the functional allocation framework when encountered. Because of the difficulty associated with managing the multitude of FRs at the extended leaf level, an automated accounting scheme is warranted.

### 5.3.3 Manning Accountability

The Navy manning structure is comprised of officers and enlisted personnel. The bridge between officers and enlisted crewmembers are Chief Petty Officers (CPO's), the senior enlisted personnel considered to be experts within a particular field. Navy manning policy currently assigns enlisted personnel to ships based on rank and job specialty, as designated by a rating. Many rating designations exist. On a simplistic level, each respective rating signifies the

requisite training and ability to perform tasks in one of the major shipboard areas: engineering, operations, combat systems, deck, and supply. Officer billeting is currently more flexible as most jobs require only a specific rank and surface warfare qualification. Although, some officer positions require a naval officer's billeting code (NOBC) which signifies the requisite training and experience in a certain area.

Personnel selected to fulfill an FR are designated as either an officer, CPO, or enlisted crewmember, each with the appropriate rank and skill level (indicated by rating and NOBC, if necessary). For example, the FR stated as "*Read pressure gage*" is fulfilled by the DP "*E-5 GSM.*" E-5 indicates enlisted, fifth paygrade and GSM is the gas turbine mechanic rating. Because personnel are capable of multi-tasking, it is not only conceivable, but also most probable, that a single human will satisfy multiple tasks during the same state. Having sensory perception and cognitive skills, humans are a physically integrated DP. Since all functions performed by the human do not require simultaneous satisfaction, physical integration is possible without compromising functional independence [18]. Therefore, the Independence Axiom still is satisfied provided overtasking does not exist.

Since the manning and automation combination meeting the mission need for the least cost is desired, all conceivable combinations must be analyzed. The cost of a completely manned ship is first determined as the baseline for comparison. In other words, at each tradoff node, a crewmember is selected as the DP. To completely functionally determine the ship's manning, a method to track the selected DPs which augments the function tracking scheme is necessary. The following method meets this need.

Since the manning level is based on all anticipated states, all states must be evaluated prior to removing a single person for replacement with automated technologies. For each state, complete the extended decomposition as required selecting only personnel as DPs. Then, tabulate all FR/DP pairs. At the end of this process, the FR/DP pairs are known for each operating scenario (state). Not all personnel fulfill functions in all states. Personnel utilized in one state, but not in others must still be accounted for in all states under the designation "not functionally required." Not doing so misses a potential tradeoff as described next.

The tabulated DPs are the ship's feasible manning level since fulfillment of all FRs in all states results. Now, the focus shifts to determine how much the crew can be reduced with-

out sacrificing mission effectiveness. For this process, both existing and potential automated technologies are considered. As each technology is presented, the DPs designated as personnel are replaced with candidate systems when applicable. The goal is to introduce systems which replace the functionality of the same human across all states. For a single person to be removed from the ship, all assigned functions in all states must be removed. For example, if the DP "*E-5 GSM*" is replaced by a candidate system in one state, removal is warranted only if all other "*E-5 GSM*" functions are similarly fulfilled by automated technology.

All personnel are accounted for in all states because if a certain rating is only required in a few states, that rating is not critical. Therefore systems should be developed to target these areas. Another possibility is to replace different personnel in different states, remove some of the crewmembers, and shift FR fulfillment responsibility amongst the remaining crewmembers. This is only feasible for non-rate specific tasks, unless Navy training philosophy shifts to foster more diversified task accomplishment. Based on the complexity associated with this process, an automated DP tracking scheme must be developed and implemented in conjunction with the FR tracking scheme.

### 5.3.4 Selection of Automated Technologies

Automated systems come in many forms and are designed to fulfill numerous functional requirements. Currently many automated technologies are employed on commercial seagoing vessels. These technologies allow commercial crews consisting of typically 25 crewmembers to accomplish all necessary functions inherent to large displacement ship operations. Many systems employed on naval vessels are also equipped with automated features, but most still require monitoring and manual intervention based on outdated operational doctrine as discussed in Section 5.1. Additionally, the reduced manning initiative has produced advanced technology demonstrators (ATD's) designed to prove highly automated technologies on naval vessels at sea. The fact remains that technology capable of fulfilling a wide array of FRs exists today.

In addition, several technologies have been conceptually designed to support the Navy's perceived needs. These conceptual designs advance current technology and directly address the intent of the reduced ship manning initiative. Some specific examples are in the areas of ship control, combat systems responsiveness, unmanned deck operations, engineering systems

remote monitoring, and advanced damage control methods. In today's technologically superior climate, conjecture suggests that an enabling technology can probably be envisioned, designed, and produced to fulfill almost any well defined functional need.

Now, a means of identifying the most beneficial areas to concentrate research and development efforts must be determined. A scientific based, rigorous methodology based on axiomatic design theory has been proposed to meet this need. Implemented properly, this functional allocation approach determines the correct mixture of functions requiring fulfillment with automated methods by evaluating the functional requirements of all operational states. By using this approach, the functional requirements determine the necessary automated technologies, as opposed to the automated technologies driving the requirements.

## 5.4 DD13A Case Study

A case study is conducted to prove the proposed functional allocation approach. For this approach to be considered successful, the overall ship impact must be demonstrated as tradeoffs are made. The complete approach requires evaluation of all FRs across all states considering a multitude of automation solutions, both mature and conceptual. Since this endeavor undoubtedly requires significant effort, a 'proof of concept' is actually presented. Thus, an evaluation of $FR_1$, move through the water, satisfied by $DP_1$, the propulsion system, is evaluated only in the peacetime steaming state, Condition IV. Existing automated systems are implemented.

The baseline for comparison is the DD13A designed using the MIT XIII-A Functional Ship Synthesis Model. Section 4.3 discusses design of the DD13A. Appendix C contains the actual ship design. The manning level of this baseline was not determined using the functional allocation approach. But, crewmember DPs are considered to fully satisfy all extended decomposition FRs. Since only $DP_1$ is decomposed further, the manning level of the personnel required to fulfill all $FR_1$ tradeoff node functions is additionally required.

Based on current U.S. Navy gas turbine propelled ship operating procedures, the following assumptions are made regarding the baseline DD13A engineering watch section manning. Overall engineering control and monitoring is located in the central control station (CCS) where the engineering officer of the watch (EOOW) oversees all engineering functions. The propul-

sion control station operator assists the EOOW and monitors the propulsion plant from CCS. The propulsion control station operator also maintains local propulsion control. Because the DD13A is powered by four gas turbines, and based on survivability concerns, two main engine rooms (main spaces) are required. Each main space requires two personnel to locally monitor the contained machinery and ensure space cleanliness and safety. Finally, a "roving watch" assists all watch personnel and monitors unmanned spaces, such as the 'shaft alleys,' the spaces the propeller shafts transit through before exiting the ship hull.

Therefore, the typical watch section consists of seven personnel. Since crewmembers require rest and also must perform additional duties, three sets of engineers, engineering watch sections, divide the watch duties throughout the day. Assuming each watch section also contains two crewmembers in training, 27 watchstanders are assigned to the main propulsion division. There exists the possibility to significantly reduce the engineering manning.

The functional allocation procedure is used to eliminate personnel for replacement with automated systems if supported by the extended decomposition, and the necessary technology is identified. As stated above, all the functions preformed by the crewmember in all the states must be fulfilled by candidate systems, or restructuring of task assignment, before the subject crewmember legitimately can be removed from the ship without adverse repercussions. In this simplified analysis, it is assumed that analyses of all $FR_1$ associated duties are complete in all other states, and removal of any/all personnel is justified if the Condition IV lower level FRs are satisfied by alternate methods. Of course, this is quite a simplifying assumption.

### 5.4.1 Extended Decomposition of $FR_1$

The cornerstone of the functional allocation process is determining the functions requiring fulfillment at the tradeoff nodes. The tradeoff nodes are found at the leaf level of the existing design hierarchy. The $FR_1$ branch is developed in Subsection 3.4.1. Commonality of components exists throughout the engineering systems as indicated by the *typical fluid system* and *typical electrical system* designations utilized during the hierarchy development (again, see Subsection 3.4.1).

When evaluating the leaf level nodes, these typical systems primarily become the basis for tradeoffs. Specifically, the following DPs repeatedly require decomposition in greater detail:

valves, gages, and control panels. Gages measure pressures, temperatures, and quantities. Quantity gages also include tank level indicators and sight glasses. Rather than list all the decomposed tradeoff nodes individually, and again relying on commonality between systems, three 'typical' decompositions, the *typical valve*, the *typical gage*, and the *typical control panel*, are implemented.

At all tradeoff nodes, automated systems are selected to fulfill the FRs whenever possible. All automated systems implemented to replace personnel currently exist. No additional systems are proposed during the course of this analysis. In all, five systems with associated features become the selected DPs. All of these automated system DPs have proved reliable at sea operationally deployed in the USNS Gordon, a large displacement military sealift vessel [14]. Because multiple functionality is imbedded in the decision algorithms and protocols of these systems, numerous FRs are fulfilled simultaneously by each technology while maintaining functional independence. Each utilized automation technology controls and monitors a respective system. The systems benefitting from the automation are the start air system (also incorporating the clutch air system and the propulsion control air system), the reduction gear lube oil system, the fuel system, the main engine cooling system (both lube oil and sea water systems), and the controllable pitch propeller (CPP) hydraulic system.

Prior to presenting the common decompositions, the affected tradeoff nodes are listed below sorted by DP designation.

| *typical valve* | *typical gage* | | | | *typical control panel* |
|---|---|---|---|---|---|
| $DP_{1.1.1.3}$ | $DP_{1.1.1.5}$ | (p) | $DP_{1.2.2.6}$ | (p) | $DP_{1.1.1.1.2}$ |
| $DP_{1.1.2.3}$ | $DP_{1.1.2.5}$ | (p) | $DP_{1.2.2.7}$ | (q) | $DP_{1.1.3.8.2.2}$ |
| $DP_{1.1.3.3}$ | $DP_{1.1.3.5}$ | (q) | $DP_{1.2.2.8}$ | (T) | $DP_{1.2.2.2.2}$ |
| $DP_{1.1.3.8.3}$ | $DP_{1.1.3.6}$ | (p) | $DP_{1.2.2.9.5}$ | (p) | $DP_{1.2.2.9.2.2}$ |
| $DP_{1.2.1.1.2}$ | $DP_{1.1.3.7}$ | (T) | $DP_{1.3.2.2.6}$ | (q) | $DP_{1.2.2.10.2}$ |
| $DP_{1.2.2.4}$ | $DP_{1.1.3.8.5}$ | (p) | $DP_{1.3.2.2.7}$ | (p) | $DP_{1.3.2.2.2.2}$ |
| $DP_{1.2.2.9.3}$ | $DP_{1.2.1.1.4}$ | (p) | $DP_{1.4.3.5}$ | (p) | $DP_{1.3.2.2.4.2}$ |
| $DP_{1.3.2.2.3}$ | | | | | $DP_{1.4.3.1.2}$ |
| $DP_{1.4.3.3}$ | | | | | |

Since entire systems are affected by the selected technologies, the third, or fourth, tier parent DP (system) growing to each tradeoff node is stated along with the fulfilled FR. After listing these parent DPs, the typical FR/DP set of the start air system ($DP_{1.1.1}$) originating from the tradeoff node is given. The decomposition between the respective parent DP and the tradeoff node is not reiterated. Similar decompositions applies to the other four automated systems. Because no significant differences exist, only the $DP_{1.1.1}$ extension is shown in detail. Appendix B reflects the design hierarchy extension of all tradeoff nodes.

| | |
|---|---|
| $FR_{1.1.1}$ = Provide inertia to start engine | $DP_{1.1.1}$ = Starting air system |
| $FR_{1.1.2}$ = Provide fuel for continuous engine operation | $DP_{1.1.2}$ = MPE fuel system |
| $FR_{1.1.3}$ = Cool engine | $DP_{1.1.3}$ = MPE lube oil system |
| $FR_{1.2.2}$ = Cool reduction gear | $DP_{1.2.2}$ = Lube oil system |
| $FR_{1.2.1.1}$ = Activate / de-activate clutch | $DP_{1.2.1.1}$ = Clutch air system |
| $FR_{1.3.2.2}$ = Control pitch angle | $DP_{1.3.2.2}$ = CPP hydraulic system |
| $FR_{1.4.3}$ = Produce desired engine speed / propeller pitch combination | $DP_{1.4.3}$ = Propulsion control air system |

Manning and automation decisions are required to satisfy to decomposed functions of $DP_{1.1.1.3}$, $DP_{1.1.1.5}$, $DP_{1.1.1.1.2}$. These DPs respectively are the *typical valve*, the *typical gage*, and the *typical control panel*. As stated, the selected automated systems possess the capability to provide functionally independent fulfillment of the respective FRs as follows starting with $DP_{1.1.1.3}$. The FR/DP pairs are listed followed by the design equations (Equation 5.1).

| | |
|---|---|
| $FR_{1.1.1.3}$ = Start / stop air flow | $DP_{1.1.1.3}$ = Valves |
| $FR_{1.1.1.3.1}$ = Open / close valves | $DP_{1.1.1.3.1}$ = Automated start air system electrical relays |
| $FR_{1.1.1.3.2}$ = Verify valve alignment | $DP_{1.1.1.3.2}$ = Automated start air system sensors |
| $FR_{1.1.1.3.3}$ = Report valve alignment | $DP_{1.1.1.3.3}$ = Automated start air system display panel |

$$\begin{Bmatrix} FR_{1.1.1.3.1} \\ FR_{1.1.1.3.2} \\ FR_{1.1.1.3.3} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.1.3.1} \\ DP_{1.1.1.3.2} \\ DP_{1.1.1.3.3} \end{Bmatrix} \tag{5.1}$$

The start air valves, as with all system valves, must be opened and closed ($FR_{1.1.1.3.1}$) to support the transfer or securing of air flow depending on the situation. When activated, the automated start air system relays ($DP_{1.1.1.3.1}$) transmit the necessary electric signal causing activation. To ensure proper operating configuration, valve alignment must first be verified ($FR_{1.1.1.3.2}$), and the reported ($FR_{1.1.1.3.3}$). Integral sensors within the automated system ($DP_{1.1.1.3.2}$) verify alignment of all pertinent valves and the query results are visually shown on a display panel ($DP_{1.1.1.3.3}$) located in CCS. Valve alignment must be determined prior to display. Therefore, $DP_{1.1.1.3.2}$ affects $FR_{1.1.1.3.3}$.

Next, $DP_{1.1.1.5}$, the various start air system pressure gages, is decomposed. The designed features of the automated start air system fulfill the five FRs as shown in Equation 5.2, the design equations.

| | |
|---|---|
| $FR_{1.1.1.5}$ = Determine air pressure | $DP_{1.1.1.5}$ = Pressure gages |
| $FR_{1.1.1.5.1}$ = Read gages | $DP_{1.1.1.5.1}$ = Automated start air system pressure sensors |
| $FR_{1.1.1.5.2}$ = Record gage pressures | $DP_{1.1.1.5.2}$ = Automated start air system memory bank |
| $FR_{1.1.1.5.3}$ = Report gage pressures | $DP_{1.1.1.5.3}$ = Automated start air system display panel |
| $FR_{1.1.1.5.4}$ = Determine if pressure is within specifications | $DP_{1.1.1.5.4}$ = Automated start air system programmed pressure database |
| $FR_{1.1.1.5.5}$ = Respond to correct potential casualty | $DP_{1.1.1.5.5}$ = Automated start air system mechanical casualty control protocol |

$$\begin{Bmatrix} FR_{1.1.1.5.1} \\ FR_{1.1.1.5.2} \\ FR_{1.1.1.5.3} \\ FR_{1.1.1.5.4} \\ FR_{1.1.1.5.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ X & X & O & O & O \\ X & X & X & O & O \\ X & O & O & X & O \\ O & O & O & X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.1.5.1} \\ DP_{1.1.1.5.2} \\ DP_{1.1.1.5.3} \\ DP_{1.1.1.5.4} \\ DP_{1.1.1.5.5} \end{Bmatrix} \tag{5.2}$$

The fulfillment of $FR_{1.1.1.5.1}$, read gages, and $FR_{1.1.1.5.3}$, report gage pressures, respectively by pressure sensors ($DP_{1.1.1.5.1}$) and the system display panel ($DP_{1.1.1.5.3}$) parallels the reasoning stated above. Therefore, no additional discussion ensues. Gage pressures must be recorded ($FR_{1.1.1.5.2}$) for system performance trend analysis. By studying the readings contained in the system memory bank ($DP_{1.1.1.5.2}$), impending failure caused by component degradation may be prevented. By accessing a programmed database ($DP_{1.1.1.5.4}$), the automated system determines if system pressure is within the prescribed range ($FR_{1.1.1.5.4}$). If not, the potential for casualty exists. The designed mechanical casualty control protocol ($DP_{1.1.1.5.5}$) must be able to respond ($FR_{1.1.1.5.5}$) before loss of the system occurs. Functional couplings occur between the various DPs, but the overall design satisfies the Independence Axiom.

The last example of a typical DP is $DP_{1.1.1.1.2}$, a control panel. Equation 5.3, the design equations, shows that all FRs determined from the tradeoff node are fulfilled in a decoupled manner.

$FR_{1.1.1.1.2}$ = Energize / de-energize

$DP_{1.1.1.1.2}$ = Control panel

$FR_{1.1.1.1.2.1}$ = Actuate / terminate system operation

$DP_{1.1.1.1.2.1}$ = Automated start air system electrical switch

$FR_{1.1.1.1.2.2}$ = Read system voltage and current

$DP_{1.1.1.1.2.2}$ = Automated start air system internal volt/amp-meter

$FR_{1.1.1.1.2.3}$ = Determine if electrical parameters are within specifications

$DP_{1.1.1.1.2.3}$ = Automated start air system programmed electrical database

$FR_{1.1.1.1.2.4}$ = Respond to correct potential casualty

$DP_{1.1.1.1.2.4}$ = Automated start air system electrical casualty control protocol

$$\begin{Bmatrix} FR_{1.1.1.1.2.1} \\ FR_{1.1.1.1.2.2} \\ FR_{1.1.1.1.2.3} \\ FR_{1.1.1.1.2.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & X & X & O \\ O & O & X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.1.1.2.1} \\ DP_{1.1.1.1.2.2} \\ DP_{1.1.1.1.2.3} \\ DP_{1.1.1.1.2.4} \end{Bmatrix} \tag{5.3}$$

The control panel receives power from the ship's electrical system. But in order for the start air system to actuate ($FR_{1.1.1.1.2.1}$), an electrical connection must be made via closing of the appropriate switch ($DP_{1.1.1.1.2.1}$). Likewise, termination of system power happens when the switch is open. An internal volt/amp-meter ($DP_{1.1.1.1.2.2}$) reads the important system parameters ($FR_{1.1.1.1.2.2}$). If either voltage, or current is out of specification ($FR_{1.1.1.1.2.3}$) according to the programmed electrical database ($DP_{1.1.1.1.2.3}$), the potential for casualty exists. Therefore, the electrical casualty control protocol ($DP_{1.1.1.1.2.4}$) must respond in a timely manner ($FR_{1.1.1.1.2.4}$) to prevent further system degradation, or loss of the entire system. Once again, functional couplings occur between the various DPs, but the overall decomposition satisfies the Independence Axiom.

Tradeoff nodes originating from the $DP_{1.4}$ and $DP_{1.5}$ branches also require addressing. $DP_{1.4}$, the engineering operation station, decomposes to include $DP_{1.4.1}$, throttle control, and $DP_{1.4.2}$, indicator gage. Both these DPs have simple decompositions of two associated FRs. All four functions are assigned to a single watchstander, a Chief Gas Turbine Mechanic, as indicated. Equations 5.4 and 5.5 are both respective design equations. Because overtasking is not anticipated, functional independence is maintained.

$FR_{1.4.1.1}$ = Receive propulsion order $\quad$ $DP_{1.4.1.1}$ = CPO GSM

$FR_{1.4.1.2}$ = Implement propulsion order $\quad$ $DP_{1.4.1.2}$ = CPO GSM

$$\begin{Bmatrix} FR_{1.4.1.1} \\ FR_{1.4.1.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.4.1.1} \\ DP_{1.4.1.2} \end{Bmatrix} \tag{5.4}$$

$FR_{1.4.2.1}$ = Read indicator gage $DP_{1.4.2.1}$ = CPO GSM

$FR_{1.4.2.2}$ = Verify proper pressure corresponding to propulsion prder $DP_{1.4.2.2}$ = CPO GSM

$$\begin{Bmatrix} FR_{1.4.2.1} \\ FR_{1.4.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.4.2.1} \\ DP_{1.4.2.2} \end{Bmatrix} \tag{5.5}$$

The watchstander must also fulfill the decomposed functions of $DP_{1.4.3.6}$, the transfer valve. The other propulsion control air system tradeoff node functions are allocated to the selected automated air system. The transfer valve is contained in CCS and is used to shift propulsion control between the engineering operations station (EOS) and the lee helm, located on the bridge. A lee helmsman is stationed on the bridge and fulfills the same pair of functions discussed directly above. The final FR/DP pairs are listed with the decoupled design equations (Equation 5.6) mapping the required functions into the physical domain.

$FR_{1.4.3.6.1}$ = Position transfer valve to achieve local / remote control $DP_{1.4.3.6.1}$ = CPO GSM

$FR_{1.4.3.6.2}$ = Verify control received by proper station $DP_{1.4.3.6.2}$ = CPO GSM

$$\begin{Bmatrix} FR_{1.4.3.6.1} \\ FR_{1.4.3.6.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1.4.3.6.1} \\ DP_{1.4.3.6.2} \end{Bmatrix} \tag{5.6}$$

Based on the rigorous functional allocation analysis, the Condition IV engineering watch section is reduced from nine personnel to a single watchstander positioned in CCS. The lee helmsman also contributes to fulfilling $FR_1$ and is not replaced by automated technology, but is not considered a member of the engineering watch team. Recalling the three section watch rotation, a total of 24 enlisted crewmembers can feasibly be removed from the ship without adversely affecting operational readiness. The removal of these crewmembers results in a total complement of 126, reflecting a 16% reduction in crew size. This is only valid for this simplified 'proof of concept.' Any legitimate manning analysis must consider all anticipated operational states.

### 5.4.2 Implementation

One feasible manning and automation combination has been determined using the outlined functional allocation approach. Now, the implications of the tradoffs must be evaluated. To this end, a reduced manned, more automated DD13A variant is designed using the functional math model. This variant, called the DD13A-X, must satisfy the identical customer attributes listed in Section 4.3.

The automated systems must be accounted for in the ship modelling procedure. Because no specific 'hard data' was obtained to assist system representation, assumptions are necessary. The intent of this comparison is to demonstrate the effectiveness of the proposed methodology, not to produce the definitive cost associated with the manning and automation decisions. Therefore, the automated system characteristics assumptions are arbitrary, but definitely reasonable.

These systems require negligible space as compared to the overall main propulsion configuration. In fact, most of the automated technologies imbed into existing machinery and system equipment. The only component requiring additional space is the monitoring and control console utilized in conjunction with all the selected automated systems. This console occupies an estimated 50 ft$^2$ in CCS. The selected systems are also relatively light, once again as compared to the existing configuration. The estimated weight for all automated systems and components is only 1 lton. And, although the systems are electrically powered, the combined power consumption requirement is relatively small at an estimated 5 kW.

Cost is important to the evaluation process. Therefore, it cannot be neglected. The cost of each individual automated system is not included, but rather a combined system cost is utilized. The total cost is divided into two main contributors, actual hardware and software, plus installation and testing. Hardware and software cost an estimated $ 500,000. Installation and testing cost an estimated $ 5 million. The weight based cost model accounts for these specific costs, as well as the system weights.

The functional math model is modified to reflect the addition of the selected automated systems and used to synthesize the DD13A-X. In addition to meeting the same CAs, the DD13A-X is configured with the same weapons configuration. Therefore mission effectiveness equals the baseline capabilities. Appendix D contains the completely synthesized reduced

crew size variant.

### 5.4.3 Results

Since ships are seldom built as 'one of a kind,' an entire program supporting the construction of 20 ships is evaluated. The class of respectively, DD13A's and DD13A-X's are assumed to operate over the same life cycle, 2,500 operating hours per year for a 30 year service life. For analysis purposes, the initial operational capability (IOC) of both ship classes is 2010, and three ships are built per year. The IOC signifies the first in class has been thoroughly evaluated and deemed ready for fleet operations. A summary comparing the DD13A with the DD13A-X is given below highlighting the important ship characteristics and costs.

| | DD13A | DD13A-X | % Difference |
|---|---|---|---|
| Total crew | 150 | 126 | −16.0 |
| $\Delta_{FL}$ | 7,457 lton | 7,421 lton | −0.5 |
| $LWL$ | 501 ft | 501 ft | – |
| $B$ | 54 ft | 54 ft | – |
| $T$ | 18.6 ft | 18.5 ft | −0.5 |
| $D_{10}$ | 37.0 ft | 37.0 ft | – |
| $C_P$ | 0.61 | 0.61 | – |
| $C_X$ | 0.85 | 0.85 | – |
| $V_{TA}$ | 542,577 ft$^3$ | 529,313 ft | −2.4 |
| $A_{TA}$ | 60,286 ft$^2$ | 58,813 ft$^2$ | −2.4 |
| Req'd Propulsion Power | 86,949 hp | 86,867 hp | −0.1 |
| Req'd Electrical Power | 8,514 kW | 8,438 kW | −0.9 |
| Total Lead Ship Acquisition Cost | \$ 820.43$M$ | \$ 826.45$M$ | 0.7 |
| Average Ship Acquisition Cost | \$ 668.68$M$ | \$ 668.51$M$ | −0.03 |
| Undiscounted Personnel LCC | \$ 2.05$B$ | \$ 1.76$B$ | −14.1 |
| Total Program Undiscounted LCC | \$ 37.16$B$ | \$ 36.52$B$ | −1.7 |
| Total Program Discounted LCC | \$ 4.76$B$ | \$ 4.73$B$ | −0.6 |

Although the DD13A-X is somewhat smaller than the DD13A, the sizes are comparable. The noticeable effect of the functional allocation decisions is seen when comparing the three

associated costs. Because of the initial high costs associated with test and evaluation (T & E) of the militarized automated systems, the DD13A-X is more expensive as indicated by the higher total lead ship acquisition cost. But, as the systems become more proven in the naval environment, these T & E costs diminish. Thus, over the entire project acquisition, the average cost becomes cheaper because the ships are slightly smaller.

Throughout the life cycle, as expected, the personnel costs associated with the DD13A-X program are significantly lower than those of the DD13A program. These lower personnel costs more than compensates for the initial high costs of the increased automated capabilities resulting in a lower DD13A-X undiscounted total program cost. To determine the true impact of the manning and automation decisions, the entire life cycle must be analyzed such that the effects are realized in the present time. Therefore, the total program cost must be accurately calculated in today's dollars by applying a discount rate. Following standard government practice, a discount rate of 10% is used, which signifies a willingness to commit to long-term projects (such as ship building programs). The discount rate represents the fact that money now is worth more than money in the future, and permits the comparison of costs incurred at different times [7]. By removing 16% of the baseline crew and fulfilling the vacated functions with automated monitoring and control systems, total life cycle cost savings are realized primarily due to eliminating the costs associated with the removed crewmembers.

## 5.5 Summary

It is possible to extend the ship design methodology developed in Chapter 3 to include the allocation of functions between humans and automated machines. The utility of this axiomatic design based methodology is demonstrated through a 'proof of concept.' This rigorous functional allocation approach does not rely upon conjecture. That is, a target manning level is not required to initiate the process. But rather, the process determines the feasible manning level. Thus, the iteration frequently involved with developing reduced crew manning plans is removed. Additionally, by studying the functional assignment of tasks, the most beneficial areas for new technology developments are seen.

Before crewmembers are removed from the ship, all operating scenarios must be evaluated.

An unnecessary human during one scenario may prove to be the key contributor in another situation. Because shipboard functional requirements are often time variant, the ship must be treated as a large flexible system. After completing analysis of all functional areas in all anticipated states, logical manning and automation tradeoffs are possible. Then, at the conceptual level of design, manifesting these decisions into the functional math model to synthesize the envisioned design reveals the overall impact on ship characteristics and cost.

# Chapter 6

# Conclusions

Thus ends the study investigating the functional design of a generic multi-mission capable concept level warship. Multi-mission indicates multi-function, therefore many factors pertinent to a wide array of ships are addressed by this analysis. A better understanding of the application of axiomatic design theory to large systems also results from this endeavor.

## 6.1 Contributions

The insight gained from this rigorous analysis represents contributions in two areas pertinent to the U.S. Navy, concept level ship design and the functional allocation process. The perceived contributions to each field follow. Also included are the perceived contributions to axiomatic design.

### 6.1.1 Concept Ship Design

The axiomatic approach to design provides a means to conduct functional vice physical ship design. Adhering to the design progression defined by the numerous design equations, starting with the most general, highest level functional definitions and increasing in detail as the design decomposes, results in the complete design of a warship. This scientific based methodology identifies functions requiring fulfillment, presents physical design parameters to meet these needs, and maps the interrelationship between the two. Therefore, in theory, couplings between parameters are known *a priori*. Since the design equations exactly list the best order for

functional satisfaction, the *ad hoc* approach to ship design is no longer necessary at the concept level. The 'Design Spiral' is effectively replaced with the hierarchial set of design equations.

Current naval architecture practices specify design of the hull first. Then, all necessary systems are forced to fit within the physical hull confines. The AAD based approach proposes the exact opposite design approach to control couplings. In other words, the systems are designed first, and then the hull is designed to enclose the cumulative system volume and area. Therefore, when implemented, this approach will most likely be met with resistance from the traditional thinking ship designers.

This design methodology supports analysis of the recently proposed 'modular-mission' ships. In this context, modular means a physical module containing a specific mission package. For example, these modules contain strike missile launching systems, mine hunting equipment, etc. As mission requirements change, the ship reconfigures with the appropriate module while in port and then transits to the mission area. In other words, the ship is only required to fulfill a subset of possible warfare missions at a given time. This modularity is useful to allow risk mitigation as new technologies are developed during the design process, as well as providing the same technology insertion capability over the ship lifetime. The generic surface combatant evaluated during this study is a multi-mission platform. Therefore, individual branches of the $FR_3$, neutralize enemy targets, decomposition support the study of modular-mission ships. The overall ship effect resulting from the addition and subtraction of functions can readily be assessed.

The functional math model is a significant improvement to the existing math model. The salient features of this enhanced ship synthesis tool include reduced iteration, exact ordering of design parameter specification, automated accounting of mission payload parameters, and complete single pass convergence of area, volume, weight, and electrical powering design. The automated accounting of payload parameters paves to way for a completely integrated ship design tool connecting a product data manager (PDM) with a computer aided design (CAD) package.

### 6.1.2 Shipboard Functional Allocation Procedure

A framework for rigorously identifying functions prior to identifying automated technologies is developed and demonstrated. By following the outlined functional allocation approach, areas requiring technology improvement are identified. By doing so, time and effort is not expended developing systems to enhance unnecessary areas. This approach ensures the functional requirements are driving the technology advancements, and not vice versa.

Axiomatic design theory reveals that the ship is, in fact, a large flexible system. Time variant functional requirements result due to either internally, or externally, driven state changes. To ensure mission effectiveness is not compromised as personnel are removed from the ship, the functional requirements in all states must be considered and fulfilled. Therefore, to justify removing personnel, all assigned functions in all states must first be allocated to another resources. U.S. Navy program offices must be aware of this fact before designating a 'target' manning level. By performing tradeoffs at the extended leaf nodes and carefully tracking functions and personnel, determination of the elusive 'optimum' manning and automation point is possible.

### 6.1.3 Axiomatic Design

The warship is a large system as defined in the axiomatic design framework. In other words, a ship fulfills numerous functional requirements simultaneously. The ship is also a flexible system because of the time variant nature of the FR sets. This study primarily addresses the design of the ship as a large system, and only eludes to the flexibility issue during the functional allocation approach development.

Design quantification advances the AAD based ship design methodology. Tremendous insight into the axiomatic design process results from manifesting the design parameters into a physically realizable concept level ship design. Design quantification occurs using the 'macro' perspective as engineering expressions defining the ship are interjected at various levels of the design hierarchy. Typically, these expressions are not applied until the leaf level. Valuable lessons contributing to the overall understanding of the axiomatic design process are also learned by studying the quantification process.

The physical ramifications of specifying design parameters must always be considered. This

point may be inadvertently disregarded during conceptual ($X$ and $O$) design equation formulation. But, as the design materializes, violations of physics become evident. In addition, although constraints bound the choice of DPs, satisfaction of one constraint does not always result in a satisfactory design when multiple constraints ultimately affect the selection of the same DPs. This is clear when fulfilling $FR_6$ by designing the hull form. Specifically, in most cases, the hull parameters completely satisfy certain constraints, but not other constraints without redesign.

One final point regarding the decoupled design structure. Qualitatively, for this ship design, the tolerance associated with the DPs becomes more strict as the design progresses. Fulfillment of $FR_1 - FR_4$ occur without trouble because no tolerance, in the form of constraints, limit DP selection, with the exception of deckhouse area and volume constraint. This constraint imposes a very loose tolerance. As the design progresses to $DP_5$, two constraints restrict selection of DPs. The electrical power constraint is again very loose, but the endurance fuel constraint is not. Finally, designing the hull to fulfill $FR_6$ requires strict tolerance as indicated by difficulty in satisfying the powering, stability, and endurance fuel constraints simultaneously. In other words, the selection set of available DPs to fulfill these three constraints simultaneously is very limited because of the imposed tolerance on the collective set of contributing hull parameters.

## 6.2 Future Research

As with many time limited evolutions, the possible areas for additional evaluation exceed the allotted time. Therefore, these areas are listed for future researchers to ponder and hopefully address.

### 6.2.1 Concept Ship Design

The axiomatic design framework, as defined by the extensive decomposition and numerous design equations, creates a solid foundation for improved functional design methodology developments. The following areas require future efforts and research.

- Investigation of determining a way to alleviate the need for hull form redesign during the design process

- Improvement of the functional math model's level of detail to include longitudinal weight balance, structural strength criteria, seakeeping, maneuvering, radar cross section (RCS), arcs of fire, etc.

- Addition of advanced hull forms as DPs in the functional math model

- Extension of the AAD framework into a more advanced ship synthesis tool such as ASSET

- Development of a functional vice weight based accounting scheme to aid the DP selection process

- Integration with a product data manager capable of maintaining an extensive functional database

- Integration of an AAD based ship synthesis tool with a PDM and a CAD system to allow designers to visualize the process of selecting and positioning DPs and then literally wrapping the hull around these DPs

### 6.2.2 Shipboard Functional Allocation Procedure

The 'proof of concept' evaluating manning and automation tradeoffs for $FR_1$ child nodes in Condition IV only begins to establish a functional allocation framework. Conceptually the outlined process appears sound. But actual detailed analysis and further development are required to determine the feasibility and full utility of the AAD based approach to functional allocation. Accomplishing the following tasks contributes to this effort.

- Extend the leaf level decomposition to 'tradeoff' nodes in all FRs

- Conduct tradeoff studies based on the procedure evaluating all applicable FRs within one state

- Expand the tradeoff studies to all FRs in all states

- Identify and propose candidate systems for implementation based on a complete functional analysis

- Analyze varying combinations of manning and automation to determine the 'optimum' manning point (first within one FR, then within one state, ...)
- Develop an automated method to account for personnel and functions
- Develop an automated method to conduct tradeoff studies
- Apply the functional allocation approach to a ship undergoing modernization

### 6.2.3 Axiomatic Design

This analysis of a large system in the axiomatic design framework brought to light some issues. The following topics address these issues requiring further thought and consideration.

- Determination of the feasibility to define a more methodical approach to physically manifesting designs
- Quantitative evaluation of the relationship between tolerances and the order of DP selection in a decoupled design
- Determination of the effect of human error on the physical integration of humans fulfilling multiple functions in a large flexible system
- Assessment of the applicability of the Information Axiom to the ship design process
- Investigation into what extent setting a DP at a constant value actually compromises system performance when done so to eliminate coupling

## 6.3 Closure

Application of the axiomatic approach to design enhances the overall concept level ship design process. When the design methodology is advanced, the shipboard functional allocation process is also enhanced. Therefore, functional design, not loosely structured iterative design, should be the standard practiced by naval architects. Conceptually, the traditional 'Design Spiral' requires replacement by the extensively developed, scientifically generated decoupled design hierarchy.

# Appendix A

# MIT XIII-A Ship Synthesis Model (Baseline DD13A Modelled)

# MIT MATH MODEL - DD13A(BASELINE)

$hp \equiv \frac{33000 \cdot ft \cdot lbf}{min}$ $\quad knt \equiv 1.69 \cdot \frac{ft}{sec}$ $\quad lton \equiv 2240 \cdot lb$

## I. INPUT

**# = Primary Input Variables**

**## = Check after every iteration**

### I1. Requirements:

**Payload:** (From CS2MP.XLS, Fig 1&2) $\quad W_P := 808.72 \cdot lton$ $\quad$ **variable:** $W_{VP} := 286.57 \cdot lton$ #

**Payload VCG:** $VCG_P := 32.72 \cdot ft$ $\quad$ **Variable Payload VCG:** $VCG_{VP} := 30.37 \cdot ft$ #

**Command and Surveillance Payload:** ($W_{400}$ **less 420 and 430)** $\quad W_{P400} := 176.6 \cdot lton$ #

**Armament (all $W_{700}$):** $W_7 := 154.17 \cdot lton$ $\quad$ **Armor:** $W_{164} := 37 \cdot lton$ #

**Mission handling/support:** $W_{P500} := 42.96 \cdot lton$ $\quad$ **Mission outfit:** $W_{P600} := 7.74 \cdot lton$ #

**Ordnance:** $W_{F20} := 222.77 \cdot lton$(incl helo wt, WF23) $\quad$ **Helo Fuel:** $W_{F42} := 63.8 \cdot lton$ #

**Helo's:** $N_{HELO} := 2$ $\quad W_{F23} := 12.73 \cdot lton$

**Payload Cruise Electric Power Requirement:** $kW_{PAY} := 662.49 \cdot kW$ #

**Payload Deck Areas:**

**Deckhouse:** **C&D:** $A_{DPC} := 4115.7 \cdot ft^2$ **(W400)** #

**Armament:** $A_{DPA} := 5258 \cdot ft^2$ **(W500, W600, W700, WF20)** #

**Hull:** **C&D:** $A_{HPC} := 5787.1 \cdot ft^2$ **(W400)** #

**Armament:** $A_{HPA} := 3784 \cdot ft^2$ **(W500, W600, W700, WF20)** #

**Manning:**

**Officers:** $N_O := 15$ $\quad$ **Enlisted:** $N_E := 135$ $\quad$ **Total:** $N_T := N_E + N_O$ $\quad N_T = 150$ #

**Average deck height:** $H_{DK} := 9 \cdot ft$ #

**Sustained Speed:** $V_S = 28 \cdot knt$ $\quad$ **(Use Figure 3 as a guide in selecting $V_S$)** #

**Endurance Speed:** $V_e = 20 \cdot knt$ $\quad$ **Range:** $E = 7500 \cdot knt \cdot hr$ #

**Stores period:** $T_S := 45 \cdot day$ #

**Sonar Dome/Appendages:** **SQS-53C Sonar:** $A_{SD} := 215 \cdot ft^2$ **(SQS-56: 27ft²; SQS-53C: 215ft²)**

**water:** $W_{498} := 87.9 \cdot lton$ $\quad VCG_{498} := -1.2 \cdot ft$ $\quad$ **structure:** $W_{165} := 85.7 \cdot lton$ #

# DD13A
# PAYLOAD #2

| PAYLOAD NAME | WT KEY | WT | VCG DATUM | VCG FT AD | AREA KEY | HULL FT2 | DKHS FT2 | CRUISE KW | BATTLE KW | WT MOMENT | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| STEEL LANDING PAD [ON HULL] - SH-60 CAPABLE | W111 | 10.7 | 39.204 | 0.20 | NONE | 0 | 0 | 0 | 0 | 421.6228 | |
| 64 CELL VLS ARMOR - LEVEL III HY-80 | W164 | 28 | 42.3771 | -10 | NONE | 0 | 0 | 0 | 0 | 906.5574 | |
| MK45 GUN HY-80 ARMOR LEVEL II | W164 | 9 | 47.7541 | -8.00 | NONE | 0 | 0 | 0 | 0 | 357.7869 | |
| SQS-53C 5M BOW SONAR DOME W/MINE AVOIDANCE | W165 | 85.7 | 0 | -1.5 | | 0 | 0 | 0 | 0 | -128.55 | |
| **GROUP 100** | **WP100** | 133.4 | | | | 0 | 0 | 0 | 0 | | |
| | | | | | | | | | | | |
| CIC W/UYQ-44 & 2X LSD | W410 | 19.34 | 0 | 35.58 | A1131 | 1953 | 448 | 45.03 | 45.03 | 688.1172 | |
| NAVIGATION SYSTEM | W420 | 7.29 | 100 | 14.00 | A1132 | 0 | 848.3 | 55.99 | 53.5 | 831.06 | |
| ADV DIGITAL C4I (JTIDS, LINK 16/LINK 22/TADIXS/TACINTEL) | W440 | 37.91 | 100 | -46.84 | A1110 | 1230.6 | 1270.4 | 35.76 | 39.67 | 2015.2956 | |
| SPS-67 SURFACE SEARCH RADAR | W451 | 1.81 | 100 | -10.00 | A1121 | 0 | 70 | 8 | 0 | 162.9 | |
| SPS-49(V)5 2-D AIR SEARCH RADAR | W452 | 9.03 | 100 | -7.1 | A1121 | 0 | 553 | 15.3 | 48.4 | 838.887 | |
| MK XII AIMS IFF | W455 | 2.32 | 100 | -5.00 | NONE | 0 | 0 | 3.2 | 4 | 220.4 | |
| X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL | W456 | 4.11 | 0 | 113.00 | NONE | 0 | 0 | 220.16 | 220.16 | 464.43 | |
| SQS-53C 5M BOW SONAR DOME ELEX W/MINE AVOIDANCE | W463 | 57.7 | 0 | 9.3 | A1122 | 1942 | 0 | 39 | 39 | 536.61 | |
| SSQ-61 BATHYTHERMOGRAPH | W465 | 0.31 | 39.204 | -10.90 | A1122 | 85.5 | 0 | 0 | 0 | 8.77424 | |
| SQQ-28 SONOBUOY PROCESSING SYSTEM | W466 | 5.26 | 100 | -44.86 | NONE | 0 | 0 | 1.15 | 1.15 | 290.0364 | |
| SLQ-32[V]3 ACTIVE ECM | W472 | 4.4 | 37 | 20.60 | NONE | 0 | 0 | 6.4 | 6.4 | 253.44 | |
| AN/SLQ-25A NIXIE | W473 | 0.24 | 39.204 | -6.20 | A1142 | 200 | 0 | 3 | 4.2 | 7.92096 | |
| SLQ-32[V]3 - MK36 DLS W/6 LAUNCHERS | W474 | 0.96 | 37 | 5.39 | NONE | 0 | 0 | 2.4 | 2.4 | 40.6944 | |
| MK 86 5"/54 GFCS | W481 | 7.50 | 100 | -4.00 | A1212 | 0 | 168 | 6 | 15.4 | 720 | |
| MK92 MFCS - STIR/CORT/IADT/CEC | W482 | 6.29 | 100 | -1.40 | NONE | 0 | 0 | 50.3 | 85.8 | 620.194 | |
| VLS WEAPON CONTROL SYSTEM | W482 | 0.7 | 38.102 | 2.54 | A1220 | 56 | 310 | 13.62 | 19.69 | 28.4494 | |
| ADVANCED TOMAHAWK WEAPON CONTROL SYSTEM | W482 | 5.6 | 37 | -7.80 | NONE | 0 | 0 | 13.27 | 13.27 | 163.52 | |
| ASW CONTROL SYSTEM [ASWCS] W/SSTD | W483 | 3.75 | 37 | -12.60 | A1240 | 320 | 0 | 8.61 | 8.61 | 91.5 | |
| COMBAT DF | W495 | 8.26 | 37 | 21.00 | A1141 | 0 | 448 | 15.47 | 19.34 | 479.08 | |
| ELECTRONIC TEST & CHECKOUT | W499 | 1.1 | 42.3771 | 10.80 | NONE | 0 | 0 | 0 | 0 | 58.494755 | |
| **GROUP 400** | **WP400** | 183.88 | | | | 5787.1 | 4115.7 | 542.66 | 626.02 | | |
| | | | | | | | | | | | |
| 64-CELL VLS MAGAZINE DEWATERING SYSTEM | W529 | 7 | 38.102 | -0.46 | NONE | 0 | 0 | 0 | 0 | 263.494 | |
| LAMPS MKIII AVIATION FUEL SYS | W542 | 4.86 | 38.102 | -11.00 | A1380 | 30 | 0 | 2 | 2.9 | 131.71572 | |
| LAMPS MKIII RAST/RAST CONTROL/HELO CONTROL | W588 | 31.1 | 38.102 | -1.60 | A1312 | 219 | 33 | 4.4 | 4.4 | 1135.2122 | |
| **GROUP 500** | **WP500** | 42.96 | | | | 249 | 33 | 6.4 | 7.3 | | |
| | | | | | | | | | | | |
| SQS-53C 5M BOW SONAR DOME HULL DAMPING | W636 | 6.7 | 0 | -2.5 | NONE | 0 | 0 | 0 | 0 | -16.75 | |
| LAMPS MKIII AVIATION SHOP AND OFFICE | W665 | 1.04 | 38.102 | -4.50 | A1360 | 194 | 75 | 0 | 0 | 34.94608 | |
| **GROUP 600** | **WP600** | 7.74 | | | | 194 | 75 | 0 | 0 | | |
| | | | | | | | | | | | |
| 1X MK45 5IN/54 GUN [ERGM] | W710 | 36.8 | 47.7541 | -6.20 | A1210 | 270 | 0 | 36.18 | 37.88 | 1529.19088 | |
| 2X HARPOON SSM QUAD CANNISTER LAUNCHERS | W721 | 4.1 | 37 | 1.17 | A1220 | 0 | 0 | 0 | 1.6 | 156.497 | |
| MK41 VLS 64-CELL | W721 | 107.72 | 38.102 | 1.14 | A1220 | .128 | 0 | 69.65 | 69.65 | 4227.14824 | |
| 2X MK32 SVTT ON DECK | W750 | 5.55 | 37 | 2.20 | A1244 | 0 | 368 | 2 | 5 | 217.56 | |
| **GROUP 700** | **W7** | 154.17 | | | | 398 | 368 | 107.83 | 114.13 | | |
| | | | | | | | | | | | |
| MK45 5IN ERGM AMMO - 600 RDS | WF21 | 35.1 | 47.7541 | -28.40 | A1210 | 798 | 68 | 0 | 0 | 679.32891 | |
| MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS) | WF21 | 144 | 38.102 | 0.34 | A1220 | 1420 | 720 | 0 | 0 | 5535.648 | |
| HARPOON MISSILES -- 8 RDS IN CANNISTERS | WF21 | 3.78 | 37 | 5.00 | NONE | 0 | 0 | 0 | 0 | 158.76 | |
| MK46 LWT ASW TORPEDOES -- 6 RDS IN SVTT TUBES | WF21 | 1.36 | 37 | 2.50 | A1240 | 368 | 0 | 0 | 0 | 53.72 | |
| MK36 DLS SRBOC CANNISTERS - 100 RDS | WF21 | 2.2 | 37 | 11.60 | NONE | 0 | 0 | 0 | 0 | 106.92 | |
| SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO | WF21 | 4.1 | 37 | -6 | NONE | 0 | 0 | 0 | 0 | 127.1 | |
| LAMPS MKIII 18 X MK46 TORP & SONOBUOYS & PYRO | WF22 | 9.87 | 38.102 | 4.80 | A1374 | 0 | 588 | 0 | 0 | 423.44274 | |
| LAMPS MKIII 2 X SH-60B HELOS AND HANGAR (BASED) | WF23 | 12.73 | 38.102 | 4.50 | A1340 | 0 | 3406 | 5.6 | 5.6 | 542.32346 | |
| LAMPS MKIII AVIATION SUPPORT AND SPARES | WF26 | 9.42 | 38.102 | 5.00 | A1390 | 357 | 0 | 0 | 0 | 406.02084 | |
| BATHYTHERMOGRAPH PROBES | WF29 | 0.21 | 39.204 | -6.00 | NONE | 0 | 0 | 0 | 0 | 6.97284 | |
| **GROUP WF20** | **WF20** | 222.77 | | | | 2943 | 4782 | 5.6 | 5.6 | | |
| | | | | | | | | | | | |
| **LAMPS MKIII:AVIATION FUEL [JP-5]** | **WF42** | 63.8 | 0 | 10.4 | A1380 | 0 | 0 | 0 | 0 | 663.52 | |
| | | | | | | | | | | | |
| **VARIABLE MILITARY PAYLOAD (WF20+WF42)** | **WVP** | 286.57 | | | | | | | | | |
| | | | | | | | | | | | |
| **ARMAMENT (WP500,WP600,W7,WF20)** | | | | | | 3784 | 5258 | | | | |
| | | | | | | | | KWP | | | |
| ***TOTAL PAYLOAD*** | ***WP*** | 808.72 | | | | 9571.1 | 9373.7 | 662.49 | 753.05 | 26459.99197 | |
| | | | | | | | | | | | |
| | | | | | | | | | | 32.71835983 | VCGP |
| ***DATUM DEFINITIONS:*** | | | | | | | | | | 30.37218407 | VCVP |
| | DEPTH0 | 52.363 | | VCG P: | 32.72 | | | | | | |
| | DEPTH3 | 47.754 | | VCG VP: | 30.37 | | | | | | |
| | DEPTH6.5 | 42.377 | | | | | | | | | |
| | DEPTH10 | 37 | | | | | | | | | |
| | DEPTH15 | 38.102 | | | | | | | | | |
| | DEPTH20 | 39.204 | | | | | | | | | |
| | BL | 0 | | | | | | | | | |
| | MAST BASE | 100 | | | | | | | | | |

**Fin Stabilizers:** **(for one pair, electric power requirement = 50 kW)** $kW_{fins} := 0 \cdot kW$ #

**Hull Material: (OS: $C_{HMAT}$=1.0; HTS: $C_{HMAT}$=0.93)** $C_{HMAT} := .93$ #

**CPS: ($W_{CPS}$=30lton):** $W_{CPS} := 30 \cdot lton$ **(ie. Full CPS)** #

**Machinery:**

**Number of propellers =** $N_P := 2$ $C_{PROPD} := if(N_P > 1, 1.0, 1.2)$ $C_{PROPD} = 1$ #

**Aux Propulsion (APU):** $W_{237} := 0 \cdot lton$ $VCG_{237} := 0 \cdot ft$ #

**Propulsion Engines (PE) - standard LM2500's; Generator engines DDA501K34**

**Number and brake horsepower of propulsion engines:** $N_{PENG} := 4$ $P_{BPENG} := 22750 \cdot hp$ #

**Inlet/exhaust Xsect area for PE:** $A_{IE} := 135.2 \cdot ft^2$ $A_{PIE} := N_{PENG} \cdot A_{IE}$ $A_{PIE} = 540.8 \, ft^2$ #

**Deckhouse decks impacted by propulsion and generator inlet/exhaust:** $N_{DIE} := 2$ #

**Hull decks impacted by propulsion inlet/exhaust:** $N_{HPIE} := 0$ #

**Machinery Box:** $H_{MBMIN} := 22 \cdot ft$ $L_{MB} := 40 \cdot ft$ $H_{MB} := D_{10}$ $H_{MB} = 37 \, ft$ #

$C_P = 0.61$ $C_{MB} := \frac{L_{MB}}{LWL}$ $C_{MB} = 0.08$ **$C_{PMB}$ from Fig. 10:** $C_{PMB} := .998$ ##

**Ship Service Generators:** $N_G := 3$ $kW_G := 3000 \cdot kW$ #

**Hull decks impacted by generator inlet/exhaust:** $N_{HeIE} := 1$ #

**Specific fuel rate for generator engines:** $FR_G := .635 \cdot \frac{lb}{kW \cdot hr}$ $FR_G = 0.474 \, \frac{lb}{hp \cdot hr}$ #

**Inlet/exhaust X-sect area for gen:** $A_{GIE} := 38.4 \cdot ft^2$ $A_{eIE} := N_G \cdot A_{GIE}$ $A_{eIE} = 115.2 \, ft^2$ #

## II. GROSS CHARACTERISTICS

**Hull Principle Characteristics:** **(see Figures 5 and 6)** **Adjust in Summary Section at end of file**

$LWL = 501.267 \, ft$ $B = 53.713 \, ft$ $D_{10} = 37 \, ft$ $C_P = 0.61$ $C_X = 0.85$ #

**deckhouse volume:** $V_D = 156000 \, ft^3$ $C_{DHMAT} := 2$ #

**(Deckhouse Material: Aluminum - $C_{DHMAT}$=1; Steel - $C_{DHMAT}$=2)**

**III. Complete Principle Characteristics:**

**Choose Payload Weight Fraction from Figure 4 and Calculate Full Load Weight (1st Iteration only, set $W_{FL}$=$W_{FL1}$ in Summary section at end of file).**

$F_P := 0.10$ $W_{FL1} := \frac{W_P}{F_P}$ $W_{FL1} = 8087.2 \, lton$ #

**Specify Full Load Weight (subsequent iterations set $W_{FL}$=$W_T$ from prior iteration in Summary at end of file):**

$$W_{FL} = 7935 \cdot \text{lton}$$ ##

**Calculate Full Load Displacement and Volume at LWL:**

$$\Delta_{FL} := W_{FL} \qquad V_{FL} := \Delta_{FL} \cdot 35 \cdot \frac{\text{ft}^3}{\text{lton}} \qquad V_{FL} = 277725 \cdot \text{ft}^3$$

**Calculate Draft (LWL):**

$$T := \frac{V_{FL}}{C_P \cdot C_X \cdot LWL \cdot B} \qquad T = 19.894 \cdot \text{ft}$$

**II2. Calculate Displacement to Length Ratio and Compare to Figure 5:**

$$C_{\Delta L} := \frac{\Delta_{FL}}{\left(\frac{LWL}{100}\right)^3} \qquad C_{\Delta L} = 63 \cdot \frac{\text{lton}}{\text{ft}^3} \qquad \textbf{(45-65)}$$

**II3. Calculate Speed to Length Ratio and $C_V$:**

$$R_{VL} := \frac{V_S}{\sqrt{LWL}} \quad R_{VL} = 1.251 \cdot \frac{\text{knt}}{\text{ft}^{.5}} \qquad C_V := \frac{V_{FL}}{LWL^3} \quad C_V = 0.002205$$

**II4. Calculate Beam to Draft Ratio and Compare to Tables 1-4:**

$$C_{BT} := \frac{B}{T} \qquad C_{BT} = 2.7 \qquad \textbf{(2.8-3.7)}$$

**II5. Calculate Length to Beam Ratio:**

$$C_{LB} := \frac{LWL}{B} \qquad C_{LB} = 9.332 \qquad \textbf{(7.5-10)}$$

**III. ENERGY (Uses Taylor Standard Series (TSS)**

**References: DDS 051-1 and Taylor Reanalysis by Gertler**

**III1. Calculate TSS Resistance:**

**III1.1 Estimate propeller diameter and frontal area of ship:**

$$C_{PROPD} = 1 \qquad D_P := (.662 \cdot T + .012 \cdot LWL) \cdot C_{PROPD} \qquad D_P = 19.185 \cdot \text{ft}$$

**Frontal area of ship =** $A_W := B \cdot (3 \cdot T) \qquad A_W = 3205.669 \cdot \text{ft}^2 \qquad \rho_A := .0023817 \cdot \frac{\text{slug}}{\text{ft}^3}$

**III1.2 Seawater propereties:**

$$T_{SW} := 59 \qquad \rho_{SW} := 1.9905 \cdot \frac{\text{slug}}{\text{ft}^3} \qquad \nu_{SW} := 1.2817 \cdot 10^{-5} \cdot \frac{\text{ft}^2}{\text{sec}}$$

**III1.3 Resistance calculation parameters:**

**Correlation Allowance:** $C_A := .0004$

**Use Figure 7 with $C_P$ and $C_{BT}$ for TSS wetted surface coeficient:** $C_P = 0.61$ $C_{BT} = 2.7$ $C_{STSS} := 2.535$ ##

$S_{TSS} := C_{STSS} \cdot V_{FL}^{.5} \cdot LWL^{.5}$ $S_{TSS} = 29910.237 \circ ft^2$

**Specify or estimate actual ship surface area:** $S_S := S_{TSS}$ #

**Use Figure 8 or 9 with LWL for Appendage Drag Coeficient:** $LWL = 501.267 \circ ft$

$$C_{DAPP} := 2.75 \cdot \frac{hp \cdot 10^{-5}}{ft^2 \cdot knt^3}$$ ##

**Air Drag Coeficient:** $C_{AA} := .7$

**Power Margin Factor (margin for concept design = 10%):** $PMF := 1.1$

**III1.4 Use range of ship speeds for speed to length ratios ($R_i$). Reynold's numbers ($RN_i$) and ITTC friction ($RF_i$):**

$i := 1 .. 7$ $V_i := i \cdot 5 \cdot knt$ **Ensure range includes $V_e$ and $V_S$:** $V_6 := V_S$ $V_6 = 28 \circ knt$ ##

$V_4 := V_e$ $V_4 = 20 \circ knt$

$$R_i := \frac{V_i}{\sqrt{LWL}} \qquad R_{N_i} := LWL \cdot \frac{V_i}{\nu_{SW}} \qquad C_{F_i} := \frac{.075}{\left(\log\left(R_{N_i}\right) - 2\right)^2}$$

$$R_{F_i} := .5 \cdot \left[\rho_{SW} \cdot S_S \cdot \left(V_i\right)^2 \cdot \left(C_A + C_{F_i}\right)\right]$$

| $\frac{V_i}{knt}$ | $R_i \cdot \frac{ft^{.5}}{knt}$ | $R_{N_i}$ | $C_{F_i}$ | $\frac{R_{F_i}}{lbf}$ |
|---|---|---|---|---|
| 5 | 0.223 | $3.305 \cdot 10^8$ | 0.002 | 4601.201 |
| 10 | 0.447 | $6.61 \cdot 10^8$ | 0.002 | 17109.539 |
| 15 | 0.67 | $9.914 \cdot 10^8$ | 0.002 | 36963.326 |
| 20 | 0.893 | $1.322 \cdot 10^9$ | 0.001 | 63900.146 |
| 25 | 1.117 | $1.652 \cdot 10^9$ | 0.001 | 97747.886 |
| 28 | 1.251 | $1.851 \cdot 10^9$ | 0.001 | 121319.672 |
| 35 | 1.563 | $2.313 \cdot 10^9$ | 0.001 | 185694.96 |

**III1.5 Use Gertler with $C_P$, $C_V$, $R_i$ and $C_{BT}$ to interpolate for $C_R$ and calcualte TSS resistance:**

$C_P = 0.61 \qquad C_V = 0.002205$

$$R_i \cdot \frac{ft^{.5}}{knt} \quad \begin{array}{|c|}\hline 0.223 \\ \hline 0.447 \\ \hline 0.67 \\ \hline 0.893 \\ \hline 1.117 \\ \hline 1.251 \\ \hline 1.563 \\ \hline \end{array}$$

**$C_{BT}$=2.25** **$C_{BT}$=3.00** **$C_{BT}$=3.75**

$$C_{R2.25} := \begin{bmatrix} .00030 \\ .00030 \\ .00030 \\ .00063 \\ .00125 \\ .00259 \\ .00470 \end{bmatrix} \quad C_{R3.00} := \begin{bmatrix} .00038 \\ .00038 \\ .00041 \\ .00087 \\ .00160 \\ .00279 \\ .00495 \end{bmatrix} \quad C_{R3.75} := \begin{bmatrix} .00051 \\ .00051 \\ .00051 \\ .00086 \\ .00163 \\ .00295 \\ .00525 \end{bmatrix}$$

##

**Form Factor:** $FF := \frac{4}{3} \cdot (C_{BT} - 3) \qquad FF = -0.4$

$$C_{RTSS_i} := C_{R3.00_i} + FF \cdot \left( \frac{C_{R3.75_i} - C_{R2.25_i}}{2} \right) + FF^2 \cdot \left( \frac{C_{R2.25_i} + C_{R3.75_i}}{2} - C_{R3.00_i} \right)$$

$$C_{RTSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001 \\ 0.001 \\ 0.003 \\ 0.005 \end{bmatrix} \qquad R_{RTSS_i} := .5 \cdot \left[ \rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot C_{RTSS_i} \right] \qquad R_{RTSS} = \begin{bmatrix} 726.928 \\ 2907.713 \\ 7024.423 \\ 27342.705 \\ 79622.026 \\ 180958.65 \\ 504505.223 \end{bmatrix} \cdot lbf$$

**III2 Calculate Bare Hull Ship Resistance:** $iw := 1 .. 15$

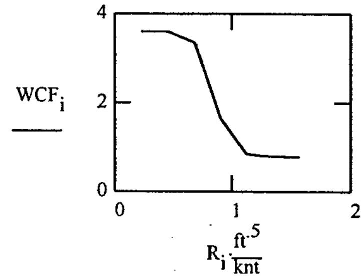
**Worm Curve data from Table 64, WCF for USN Destroyer-type Hull Forms with Bow-mounted Sonar (used):**

$$R = \begin{bmatrix} 0.223 \\ 0.447 \\ 0.67 \\ 0.893 \\ 1.117 \\ 1.251 \\ 1.563 \end{bmatrix} \cdot \frac{knt}{ft^{.5}} \qquad WCF := \begin{bmatrix} 3.60 \\ 3.60 \\ 3.35 \\ 1.65 \\ 0.85 \\ 0.81 \\ 0.78 \end{bmatrix}$$

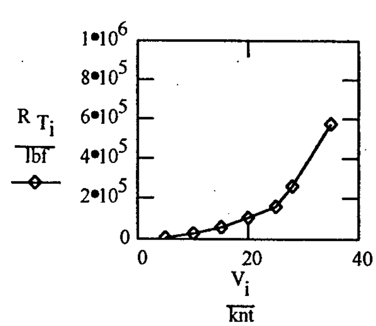
##

$$R_{R_i} := R_{RTSS_i} \cdot WCF_i$$

$$R_{T_i} := R_{F_i} + R_{R_i}$$




$$R_R = \begin{bmatrix} 2616.942 \\ 10467.767 \\ 23531.816 \\ 45115.464 \\ 67678.722 \\ 146576.506 \\ 393514.074 \end{bmatrix} \circ lbf \qquad R_T = \begin{bmatrix} 7218.143 \\ 27577.306 \\ 60495.142 \\ 109015.61 \\ 165426.608 \\ 267896.178 \\ 579209.034 \end{bmatrix} \circ lbf$$




**III3. Total Ship Effective Horsepower:**

**hull:** $P_{EBH_i} := R_{T_i} \cdot V_i$

$$\frac{P_{EBH}}{hp} = \begin{bmatrix} 110.897 \\ 847.375 \\ 2788.276 \\ 6699.505 \\ 12707.771 \\ 23048.813 \\ 62291.299 \end{bmatrix}$$

$C_{SD} := .28$

**appendage:** $P_{EAPP_i} := \left(LWL \cdot D_P \cdot C_{DAPP} + .5 \cdot C_{SD} \cdot \rho_{SW} \cdot A_{SD}\right) \cdot \left(V_i\right)^3$

$$\frac{P_{EAPP}}{hp} = \begin{bmatrix} 98.783 \\ 790.267 \\ 2667.151 \\ 6322.135 \\ 12347.92 \\ 17347.938 \\ 33882.692 \end{bmatrix}$$

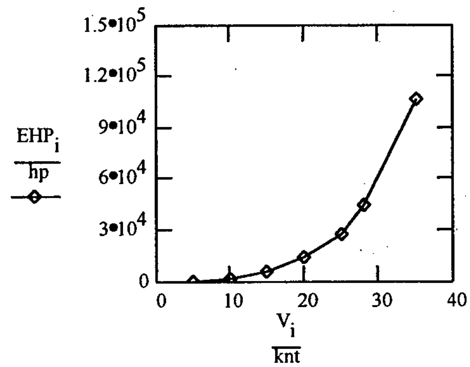
**air:** $P_{EAA_i} := .5 \cdot C_{AA} \cdot A_W \cdot \rho_A \cdot \left(V_i\right)^3$

$$\frac{P_{EAA}}{hp} = \begin{bmatrix} 2.931 \\ 23.452 \\ 79.149 \\ 187.612 \\ 366.43 \\ 514.808 \\ 1005.484 \end{bmatrix}$$

$$P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i} \qquad \frac{P_{ET}}{hp} = \begin{bmatrix} 212.612 \\ 1661.094 \\ 5534.576 \\ 13209.252 \\ 25422.121 \\ 40911.559 \\ 97179.475 \end{bmatrix}$$

$$EHP_i := PMF \cdot P_{ET_i}$$

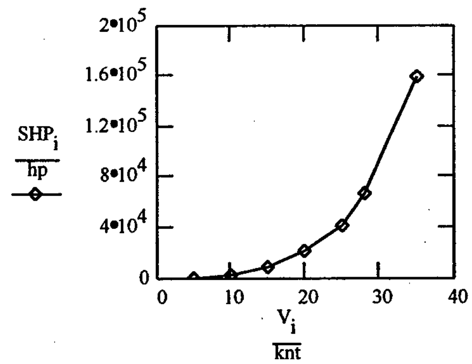
$$\frac{V_i}{knt} = \begin{array}{|c|} \hline 5 \\ \hline 10 \\ \hline 15 \\ \hline 20 \\ \hline 25 \\ \hline 28 \\ \hline 35 \\ \hline \end{array} \qquad EHP = \begin{bmatrix} 233.873 \\ 1827.203 \\ 6088.033 \\ 14530.177 \\ 27964.333 \\ 45002.715 \\ 106897.422 \end{bmatrix} \cdot hp$$




**III4. Shaft Horsepower:**

**Approximate Propulsive Coeficient (PC):** $PC := .67$ $\qquad SHP_i := \frac{EHP_i}{PC}$

$$SHP = \begin{bmatrix} 349.064 \\ 2727.169 \\ 9086.617 \\ 21686.831 \\ 41737.811 \\ 67168.231 \\ 159548.392 \end{bmatrix} \cdot hp$$




**Endurance Shaft Horsepower:** $P_e := SHP_4$ $\qquad P_e = 21686.831 \cdot hp$

**Sustained Speed Installed Shaft Horsepower Required (Allows for fouling and sea state):**

$P_S := SHP_6 \qquad P_S = 67168.231 \cdot hp \qquad P_{IREQ} := 1.25 \cdot P_S \qquad P_{IREQ} = 83960.289 \cdot hp$

**Actual installed SHP must be greater than $P_{IREQ}$**

$P_{IBRAKE} := N_{PENG} \cdot P_{BPENG}$ $\quad P_{IBRAKE} = 91000 \cdot hp$ $\quad \eta := .97$ $\quad P_I := \eta \cdot P_{IBRAKE}$ $\quad P_I = 88270 \cdot hp$

**($P_I$ must be > $P_{IREQ}$)** $\quad P_{IREQ} = 83960.289 \cdot hp$ $\quad ERR_{POWER} := \dfrac{P_I - P_{IREQ}}{P_{IREQ}}$ $\quad ERR_{POWER} = 0.051$ ##ck

**III5. Estimate Propulsion Fuel Required:**
**Reference: DDS 200-1 "Calculate of Surface Ship Endurance Fuel"**

**Average Endurance Brake SHP Required (Allows for fouling and sea state):**

$$P_{eBAVG} := 1.1 \cdot \frac{P_e}{\eta} \qquad P_{eBAVG} = 24593.314 \cdot hp$$

**Specific fuel rate for propulsion engines:**
**(GT; FR for diesel = .327)**

$$FR := 1.97 \cdot \frac{lb}{hp^{.85} \cdot hr} \cdot P_{eBAVG}^{-.15} \qquad FR = 0.432 \cdot \frac{lb}{hp \cdot hr} \qquad \#$$

**(for ICR: FR=.347 lb/hphr)**

**Margin for instrumentation and machinery differences, f($P_e$/$P_I$):** $\quad f_1 := 1.04$

**Specified fuel rate:** $\quad FR_{SP} := f_1 \cdot FR$

**Average fuel rate allowing for plant deterioration:**

$$FR_{AVG} := 1.05 \cdot FR_{SP} \qquad FR_{AVG} = 0.472 \cdot \frac{lb}{hp \cdot hr}$$

**Burnable propulsion endurance fuel weight:**

$$W_{BP} := \frac{E}{V_e} \cdot \left(P_{eBAVG} \cdot FR_{AVG}\right) \qquad W_{BP} = 1943.867 \cdot lton$$

**Tailpipe allowance and propulsion endurance fuel:** $\quad TPA := .95$
**(shallow tanks)**

$$W_{FP} := \frac{W_{BP}}{TPA} \qquad W_{FP} = 2046.176 \cdot lton$$

**Allow for expansion and tank structure in required propulsion tank volume:**

$$\gamma_F := 43 \cdot \frac{ft^3}{lton} \qquad V_{FP} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{FP} \qquad V_{FP} = 94232.548 \cdot ft^3$$

**III6. Estimate electric load.**

**Reference: DDS 310-1**

**Estimate Maximum Functional Load based on parametrics for WINTER cruise condition:**

**Propulsion:** $\quad kW_P := .00466 \cdot \dfrac{kW}{hp} \cdot P_{IBRAKE}$ $\quad kW_P = 424.06 \cdot kW$

**Steering:** $\quad kW_S := .00583 \cdot \dfrac{kW}{ft^2} \cdot LWL \cdot T$ $\quad kW_S = 58.137 \cdot kW$

**Lighting:** $\quad kW_L := .0002053 \cdot \dfrac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\quad kW_L = 197.937 \cdot kW$

**Miscellaneous:** $kW_M := 46.1 \cdot kW$

**Heating:** $kW_H := .0013 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot LWL \cdot T \cdot B$ $\quad kW_H = 870.401 \, kW$

(zero if no CPS)

**Ventilation:** $kW_{CPS} := .00026 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\quad kW_{CPS} = 250.676 \, kW$

$kW_V := .19 \cdot (kW_H + kW_P) + kW_{CPS}$ $\quad kW_V = 496.623 \, kW$

**Air Conditioning:** $kW_{AC} := .67 \cdot \left( .1 \cdot kW \cdot N_T + .0015 \cdot \frac{kW}{ft^3} \cdot .47 \cdot 1.3 \cdot LWL \cdot T \cdot B + .1 \cdot kW_P \right)$

$kW_{AC} = 367.369 \, kW$

**Aux Boiler and FW:**
**(electric boiler)** $kW_B := .94 \cdot N_T \cdot kW$ $\quad kW_B = 141 \, kW$

**Firemain:** $kW_F := .0001 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\quad kW_F = 96.414 \, kW$

**Unrep and handling:** $kW_{RH} := .00002 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot LWL \cdot T \cdot B$ $\quad kW_{RH} = 13.391 \, kW$

**Aux Machinery:** $kW_A := .22 \cdot N_T \cdot kW + kW_{fins}$ $\quad kW_A = 33 \, kW$

**Services and Work Spaces:** $kW_{SERV} := .35 \cdot N_T \cdot kW$ $\quad kW_{SERV} = 52.5 \, kW$

**Non-Payload Functional Load:**

$$kW_{NP} := kW_P + kW_S + kW_L + kW_M + kW_H + kW_V + kW_{AC} + kW_B + kW_F + kW_{RH} + kW_A + kW_{SER}$$

**Maximum Functional Load:**

$kW_{MFL} := kW_{PAY} + kW_{NP}$ $\quad kW_{MFL} = 3459.423 \, kW$

**MFL with margins: (design,growth):**

$kW_{MFLM} := 1.2 \cdot 1.2 \cdot kW_{MFL}$ $\quad kW_{MFLM} = 4981.569 \, kW$

**Installed Electrical Power Required:**

**Power available per generator:** $kW_G = 3000 \, kW$

**Power required per generator:** $kW_{GREQ} := \frac{kW_{MFLM}}{(N_G - 1) \cdot .9}$ $\quad kW_{GREQ} = 2767.538 \, kW$ #ck

$$ERR_{KW} := \frac{kW_G - kW_{GREQ}}{kW_{GREQ}} \qquad ERR_{KW} = 0.084$$

**24 hour electrical load:**

$$kW_{24} := .5 \cdot (kW_{MFL} - kW_P - kW_S) + .8 \cdot (kW_P + kW_S) \qquad kW_{24} = 1874.371 \, kW$$

**with margin (design):** $kW_{24AVG} := 1.2 \cdot kW_{24}$ $\qquad kW_{24AVG} = 2249.245 \, kW$

**III7. Estimate Electric Fuel Rate:** $FR_G = 0.635 \, \frac{lb}{kW \cdot hr}$

**Margin for instrumentation and machinery differences, f($P_e$/$P_I$):** $f_{1e} := 1.04$

**Specified fuel rate:** $FR_{GSP} := f_{1e} \cdot FR_G$

**Average fuel rate allowing for plant deterioration:**

$$FR_{GAVG} := 1.05 \cdot FR_{GSP} \qquad FR_{GAVG} = 0.693 \, \frac{lb}{kW \cdot hr} \qquad FR_{GAVG} = 0.517 \, \frac{lb}{hp \cdot hr}$$

**III8. Estimate Electrical and Total fuel Required**

**Burnable electrical endurance fuel weight:**

$$W_{Be} := \frac{E}{V_e} \cdot (kW_{24AVG} \cdot FR_{GAVG}) \qquad W_{Be} = 261.106 \, lton$$

**Tailpipe allowance and electrical endurance fuel:** $TPA := .95$

**(shallow tanks)**

$$W_{Fe} := \frac{W_{Be}}{TPA} \qquad W_{Fe} = 274.848 \, lton$$

**Allow for expansion and tank structure in required electrical fuel tank volume:**

$$V_{Fe} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{Fe} \qquad V_{Fe} = 12657.579 \, ft^3$$

**Total ship fuel: (DFM)**

$$W_{F41} := W_{FP} + W_{Fe} \qquad W_{F41} = 2321.024 \, lton$$

$$V_F := V_{FP} + V_{Fe} \qquad V_F = 106890.127 \, ft^3$$

## <u>IV. Space Estimate</u>

### IVA. Available Space

#### IVA1. Underwater Hull Volume Available

$$V_{HUW} := V_{FL} \qquad V_{HUW} = 277725 \, ft^3$$

**IVA2. Sheer Line. (3 criteria)**

**1) Keep deck edge above water at 25 degree heel**

**2) Longitudinal strength**

**3) Contain machinery box height:** $H_{MBMIN} = 22 \cdot ft$

$$M := \begin{bmatrix} .21 \cdot B + T \\ \frac{LWL}{15} \\ H_{MBMIN} \end{bmatrix} \quad M = \begin{bmatrix} 31.174 \\ 33.418 \\ 22 \end{bmatrix} \cdot ft \quad D_{10MIN} := \max(M) \quad D_{10MIN} = 33.418 \cdot ft \quad D_{10} = 37 \cdot ft$$ **#ck**

$$D_{0MIN} := 1.011827 \cdot T - 6.36215 \cdot \frac{10^{-6}}{ft} \cdot LWL^2 + 2.780649 \cdot 10^{-2} \cdot LWL + T \quad D_{0MIN} = 52.363 \cdot ft \quad D_0 := D_{0MIN}$$

$$D_{20MIN} := .014 \cdot LWL \cdot \left(2.125 + 1.25 \cdot \frac{10^{-3}}{ft} \cdot LWL\right) + T \quad D_{20MIN} = 39.204 \cdot ft \quad D_{20} := D_{20MIN}$$

**IVA3. Above-Water Hull Volume**

$F_0 := D_0 - T \quad F_{10} := D_{10} - T \quad F_{20} := D_{20} - T$

$$A_{PRO} := LWL \cdot \frac{F_0 + 4 \cdot F_{10} + F_{20}}{6} \quad F_{AV} := \frac{A_{PRO}}{LWL} \quad F_{AV} = 20.034 \cdot ft$$

$D_{AV} := F_{AV} + T \quad D_{AV} = 39.928 \cdot ft$ **cubic #:** $CN := \frac{LWL \cdot B \cdot D_{AV}}{10^5 \cdot ft^3} \quad CN = 10.75$

$C_W := .236 + .836 \cdot C_P \quad C_W = 0.746$

**flare factor:** $$f_f := .714599 + .18098 \cdot \frac{D_{AV}}{T} - .018828 \cdot \left(\frac{D_{AV}}{T}\right)^2 \quad M_f := \begin{bmatrix} f_f \\ 1 \end{bmatrix} \quad f_f := \max(M_f)$$

$f_f = 1.002$

$V_{HAW} := LWL \cdot B \cdot F_{AV} \cdot C_W \cdot f_f \quad V_{HAW} = 403176.666 \cdot ft^3$

**IVA4. Total Hull Volume.**

$V_{HT} := V_{HUW} + V_{HAW} \quad V_{HT} = 680901.666 \cdot ft^3$

**IVA5. Size Deck House:**

$V_{DMAX} := .0025 \cdot LWL^3 \quad V_{DMAX} = 314880.952 \cdot ft^3$

$V_{DMIN} := .0005 \cdot LWL^3 \quad V_{DMIN} = 62976.19 \cdot ft^3 \quad V_D = 156000 \cdot ft^3$ **#ck**

**IVA6. Calculate Total Ship Volume**

$V_T := V_{HT} + V_D \quad V_T = 836901.666 \cdot ft^3$

**IVB. Space Requirement**

**IVB1. Machinery Box** (assumed near midships) $B_{MB} := B$ $B_{MB} = 53.713 \cdot ft$

$H_{MB} = 37 \cdot ft$ $L_{MB} = 40 \cdot ft$ $A_{MB} := B \cdot T \cdot C_X + B \cdot (H_{MB} - T)$ $A_{MB} = 1827.103 \cdot ft^2$

**Calculate Machinery Box Volume:**

$V_{MB} := L_{MB} \cdot A_{MB} \cdot C_{PMB}$ $V_{MB} = 72937.95 \cdot ft^3$ $V_{AUX} := 1.2 \cdot V_{MB}$ $V_{AUX} = 87525.54 \cdot ft^3$

**IVB2. Tankage**

**Helo:**

**Helo fuel weight from Payload Spreadsheet:** $W_{F42} = 63.8 \cdot lton$

**Allow for tank structure and expansion:** $\gamma_{HF} := 43. \cdot \dfrac{ft^3}{lton}$

$V_{HF} := 1.02 \cdot 1.05 \cdot W_{F42} \cdot \gamma_{HF}$ $V_{HF} = 2938.181 \cdot ft^3$

**Lube Oil:**

**LO weight:** $W_{F46} := 7.2 \cdot lton$

**Allow for tank structure and expansion:** $\gamma_{LO} := 39 \cdot \dfrac{ft^3}{lton}$

$V_{LO} := 1.02 \cdot 1.05 \cdot W_{F46} \cdot \gamma_{LO}$ $V_{LO} = 300.737 \cdot ft^3$

**Potable Water:**

**Water weight:** $W_{F52} := N_T \cdot .15 \cdot lton$ $W_{F52} = 22.5 \cdot lton$

**Allow for tank structure:** $\gamma_W := 36 \cdot \dfrac{ft^3}{lton}$

$V_W := 1.02 \cdot W_{F52} \cdot \gamma_W$

$V_W = 826.2 \cdot ft^3$

**Sewage:** $V_{SEW} := N_T \cdot 2 \cdot ft^3$ $V_{SEW} = 300 \cdot ft^3$

**Waste Oil:** $V_{WASTE} := .005 \cdot V_{FL}$ $V_{WASTE} = 1388.625 \cdot ft^3$

**Clean Balast:** $V_{BAL} := .032 \cdot V_{FL}$ $V_{BAL} := 0 \cdot ft^3$ $V_{BAL} = 0 \cdot ft^3$

**Total:** **(for compensated system)**

$V_{TK} := V_F + V_{HF} + V_{LO} + V_W + V_{SEW} + V_{WASTE} + V_{BAL}$ $V_{TK} = 112643.87 \cdot ft^3$

**IVB3. Payload Deck Areas**

**Deckhouse payload area: (including access)** $A_{DPR} := 1.15 \cdot A_{DPA} + 1.23 \cdot A_{DPC}$ $A_{DPR} = 11109.011 \cdot ft^2$

**Hull payload area: (including access)** $A_{HPR} := 1.15 \cdot A_{HPA} + 1.23 \cdot A_{HPC}$ $A_{HPR} = 11469.733 \cdot ft^2$

**IVB4. Living Deck Area**

**Deckhouse:** $A_{COXO} := 225\cdot ft^2$ $A_{DO} := 75\cdot N_O\cdot ft^2$ $A_{DO} = 1125\,ft^2$

$A_{DL} := A_{COXO} + A_{DO}$ $A_{DL} = 1350\,ft^2$

**Hull:** $A_{HAB} := 50\cdot ft^2$ $A_{HL} := \left(A_{HAB} + \frac{LWL}{100}\cdot ft\right)\cdot N_T - A_{DL}$

$A_{HL} = 6901.9\,ft^2$

**IVB5. Hull Stores**

$A_{HS} := 300\cdot ft^2 + .0158\cdot\frac{ft^2}{lb}\cdot N_T\cdot 9\cdot\frac{lb}{day}\cdot T_S$ $A_{HS} = 1259.85\,ft^2$

**IVB6. Other Ship Functions**

**Deckhouse:**

**Maintenance:**

$A_{DM} := .05\cdot(A_{DPR} + A_{DL})$ $A_{DM} = 622.951\,ft^2$

**Bridge and Chartroom:**

$A_{DB} := 16\cdot ft\cdot(B - 18\cdot ft)$ $A_{DB} = 571.41\,ft^2$

**Engine Inlet/Exhaust:**

$A_{DIE} := 1.4\cdot N_{DIE}\cdot(A_{PIE} + A_{eIE})$ $A_{DIE} = 1836.8\,ft^2$

**Hull:**

**Ship Functions:**

$A_{HSF} := 2500\cdot ft^2\cdot CN$ $A_{HSF} = 26875.952\,ft^2$

**Engine Inlet/Exhaust:**

$A_{HIE} := 1.4\cdot(N_{HPIE}\cdot A_{PIE} + N_{HeIE}\cdot A_{eIE})$ $A_{HIE} = 161.28\,ft^2$

**IVB7. Total Required Area and Volume**

**Hull:**

$A_{HR} := A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + A_{HIE}$ $A_{HR} = 46668.715\,ft^2$

$V_{HR} := H_{DK}\cdot A_{HR}$ $V_{HR} = 420018.435\,ft^3$

**Deckhouse:**

$A_{DR} := A_{DPR} + A_{DL} + A_{DM} + A_{DB} + A_{DIE}$ $A_{DR} = 15490.172\,ft^2$

$V_{DR} := H_{DK}\cdot A_{DR}$ $V_{DR} = 139411.547\,ft^3$

**Total:**

$A_{TR} := A_{HR} + A_{DR}$ $A_{TR} = 62158.887\,ft^2$

$V_{TR} := H_{DK}\cdot A_{TR}$ $V_{TR} = 559429.982\,ft^3$

**IVC. Space Balance**

$V_{D} = 156000 \cdot ft^3$ $\qquad V_{DR} = 139411.547 \cdot ft^3$

$V_{HA} := V_{HT} - V_{MB} - V_{AUX} - V_{TK} \qquad V_{HA} = 407794.306 \cdot ft^3 \qquad V_{HR} = 420018.435 \cdot ft^3$

$V_{TA} := V_{HA} + V_{D} \qquad V_{TA} = 563794.306 \cdot ft^3 \quad > \quad V_{TR} = 559429.982 \cdot ft^3$ #ck

$A_{HA} := \dfrac{V_{HA}}{H_{DK}} \qquad A_{HA} = 45310.478 \cdot ft^2 \qquad A_{HR} = 46668.715 \cdot ft^2$

$A_{DA} := \dfrac{V_{D}}{H_{DK}} \qquad A_{DA} = 17333.333 \cdot ft^2 \qquad A_{DR} = 15490.172 \cdot ft^2$

$A_{TA} := A_{DA} + A_{HA} \qquad A_{TA} = 62643.812 \cdot ft^2 \quad > \quad A_{TR} = 62158.887 \cdot ft^2$ #ck

$ERR_{VOL} := \dfrac{V_{TA} - V_{TR}}{V_{TR}} \qquad ERR_{VOL} = 0.007801 \qquad ERR_{AREA} := \dfrac{A_{TA} - A_{TR}}{A_{TR}} \qquad ERR_{AREA} = 0.007801$

**V. Weight**

**V1. Propulsion (200)**

**Basic Machinery: (230+241/242+ 250-290)** $\quad W_{BM} := P_{I} \cdot \dfrac{lb}{hp} \cdot \left[ 9.0 + 12.4 \cdot \left( P_{I} \cdot \dfrac{10^{-5}}{hp} - 1 \right)^2 \right] \qquad W_{BM} = 361.38 \cdot lton$

**Shafting: (243)** $\quad f_{S} := .33 \qquad W_{S} := .356 \cdot \dfrac{lton}{ft} \cdot LWL \cdot f_{S} \qquad W_{S} = 58.889 \cdot lton$

**($f_S$=.5 for twin screws)**

**Props: (245)**

$$W_{PR} := .05575 \cdot lb \cdot \left( \frac{D_{P}}{ft} \right)^{5.497 - \frac{.0433}{ft} \cdot D_{P}} \cdot N_{P} \qquad W_{PR} = 48.272 \cdot lton$$

**Bearings: (244)** $\quad W_{B} := .15 \cdot (W_{S} + W_{PR}) \qquad W_{B} = 16.074 \cdot lton$

**Total Shafting:** $\quad W_{ST} := W_{S} + W_{B} + W_{PR} \qquad W_{ST} = 123.234 \cdot lton$

**Total Propulsion:** $\quad W_2 := W_{BM} + W_{ST} + W_{237} \qquad W_2 = 484.614 \cdot lton$

**V2. Electrical Plant (300)**

$$W_3 := 50 \cdot lton + .03214 \cdot \frac{lton}{kW} \cdot N_{G} \cdot kW_{G} \qquad W_3 = 339.26 \cdot lton$$

**V3. Command/Control/Surveillance (400)**

**Gyro/IC/Navigation (420, 430):** $\quad W_{IC} := 4.65 \cdot CN \cdot lton \qquad W_{IC} = 49.989 \cdot lton$

**Other/Misc Group 400:** $\quad W_{CO} := 2.24 \cdot CN \cdot lton \qquad W_{CO} = 24.081 \cdot lton$

**Cabling:** $W_{CC} := .04\cdot\left(W_{P400} + W_{IC} + W_{CO}\right)$ $W_{CC} = 10.027\,\mathrm{lton}$

$$W_4 := W_{P400} + W_{IC} + W_{CO} + W_{CC} + W_{498} \qquad W_4 = 348.597\,\mathrm{lton}$$

**V4. Auxiliary Systems (500)**

**aux steam (electric aux boiler):** **hotel steam:** $Q_{HS} := 15\cdot N_T$ **distiller:** $Q_{DS} := 6.5\cdot N_T + 250$

$W_{517} := .0013\cdot\left(Q_{HS} + Q_{DS}\right)\cdot\mathrm{lton}$ $W_{517} = 4.518\,\mathrm{lton}$ **aux sys operating fluids:** $W_{598} := .000075\cdot V_T\cdot\frac{\mathrm{lto}}{\mathrm{ft}^3}$

$W_{598} = 62.768\,\mathrm{lton}$

$$W_{AUX} := \left[.000772\cdot\left(\frac{V_T}{\mathrm{ft}^3}\right)^{1.443} + 5.14\cdot\frac{V_T}{\mathrm{ft}^3} + 6.19\cdot\left(\frac{V_T}{\mathrm{ft}^3}\right)^{.7224} + 377\cdot N_T + 2.74\cdot\frac{P_I}{\mathrm{hp}}\right]\cdot 10^{-4}\cdot\mathrm{lton} + 113.8\cdot\mathrm{lton}$$

$W_{AUX} = 612.73\,\mathrm{lton}$

**environmental support:** $W_{593} := 10\cdot\mathrm{lton}$ $W_5 := W_{AUX} + W_{P500} + W_{517} + W_{593} + W_{598} + W_{CPS}$

**V5. Outfit & Furnishings (600)** $W_5 = 762.975\,\mathrm{lton}$

**Hull Fittings:** $W_{OFH} := \left(31.4 + \frac{.0003187}{\mathrm{ft}^3}\cdot V_T\right)\cdot\mathrm{lton}$ $W_{OFH} = 298.121\,\mathrm{lton}$

**Personnel-related:** $W_{OFP} := .8\cdot\left(N_T - 9.5\right)\cdot\mathrm{lton}$ $W_{OFP} = 112.4\,\mathrm{lton}$

$$W_6 := W_{OFH} + W_{OFP} + W_{P600} \qquad W_6 = 418.261\,\mathrm{lton}$$

**V6. Structure (100)**

**Hull (110-140, 160, 190):** $W_{BH} := C_{HMAT}\cdot\left(1.68341\cdot CN^2 + 167.1721\cdot CN - 103.283\right)\cdot\mathrm{lton}$

$W_{BH} = 1756.243\,\mathrm{lton}$

$$\rho_{DH} := \mathrm{if}\left(C_{DHMAT} = 1, .0007, .001429\right)$$

**Deckhouse (150):** $W_{DH} := \rho_{DH}\cdot\frac{\mathrm{lton}}{\mathrm{ft}^3}\cdot V_D$ $W_{DH} = 222.924\,\mathrm{lton}$

**Masts:** $W_{171} := .0688\cdot\frac{\mathrm{lton}}{\mathrm{ft}}\cdot LWL - 13.75\cdot\mathrm{lton}$ $W_{171} = 20.737\,\mathrm{lton}$

**Foundations:** $W_{180} := .0675\cdot W_{BM} + .072\cdot\left(W_3 + W_4 + W_5 + W_7\right)$ $W_{180} = 139.953\,\mathrm{lton}$

$$W_1 := W_{BH} + W_{DH} + W_{171} + W_{180} + W_{165} + W_{164} \qquad W_1 = 2262.558\,\mathrm{lton}$$

**V7. Single Digit Weight Summary & Weight Balance:** $i1 := 1, 2 .. 7$

**Weight margin: (Future Growth)** $W_{M24} := .1 \cdot \left(\sum_{i1} W_{i1}\right)$ $W_{M24} = 477.043 \circ \text{lton}$

**Lightship:**

$$W_{LS} := \sum_{i1} W_{i1} + W_{M24} \qquad W_{LS} = 5247.478 \circ \text{lton}$$

**Additional Loads:**

**Provisions:** $W_{F31} := N_T \cdot 9 \cdot \frac{\text{lb}}{\text{day}} \cdot T_S$ $W_{F31} = 27.121 \circ \text{lton}$

**General stores:** $W_{F32} := .0009598 \cdot \frac{\text{lton}}{\text{day}} \cdot T_S \cdot N_T$ $W_{F32} = 6.479 \circ \text{lton}$

**Crew:** $W_{F10} := 236 \cdot \text{lb} \cdot N_E + 400 \cdot \text{lb} \cdot (N_O + 1)$ $W_{F10} = 17.08 \circ \text{lton}$

$$W_T := W_{LS} + W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10} \qquad W_T = 7935.452 \circ \text{lton}$$

**Weight Balance:** $ERR_{WEIGHT} := \frac{\Delta_{FL} - W_T}{W_T}$ $ERR_{WEIGHT} = -0.000057$ **#ck**

## VI. Stability

### VI1. Calculate Light Ship Weight Group Moments:

| **Weight** | **VCG** | | **Product** |
|---|---|---|---|
| $W_{BH} = 1756.243 \circ \text{lton}$ | $VCG_1 := .527 \cdot D_{10}$ | $VCG_1 = 19.499 \circ \text{ft}$ | $P_1 := W_{BH} \cdot VCG_1$ |
| $W_{DH} = 222.924 \circ \text{lton}$ | $VCG_2 := D_{10} + 1.5 \cdot H_{DK}$ | $VCG_2 = 50.5 \circ \text{ft}$ | $P_2 := W_{DH} \cdot VCG_2$ |
| $W_{180} = 139.953 \circ \text{lton}$ | $VCG_3 := .68 \cdot D_{10}$ | $VCG_3 = 25.16 \circ \text{ft}$ | $P_3 := W_{180} \cdot VCG_3$ |
| $W_{171} = 20.737 \circ \text{lton}$ | $VCG_4 := 2.65 \cdot D_{10}$ | $VCG_4 = 98.05 \circ \text{ft}$ | $P_4 := W_{171} \cdot VCG_4$ |

$$P_{100} := P_1 + P_2 + P_3 + P_4 \qquad VCG_{100} := \frac{P_{100}}{W_1} \qquad VCG_{100} = 22.566 \circ \text{ft}$$

| | | | |
|---|---|---|---|
| $W_{BM} = 361.38 \circ \text{lton}$ | $VCG_5 := .5 \cdot D_{10}$ | $VCG_5 = 18.5 \circ \text{ft}$ | $P_5 := W_{BM} \cdot VCG_5$ |
| $W_{ST} = 123.234 \circ \text{lton}$ | $VCG_6 := 3.9 \cdot \text{ft} + .19 \cdot T$ | $VCG_6 = 7.68 \circ \text{ft}$ | $P_6 := W_{ST} \cdot VCG_6$ |
| $W_{237} = 0 \circ \text{lton}$ | $VCG_7 := VCG_{237}$ | $VCG_7 = 0 \circ \text{ft}$ | $P_7 := W_{237} \cdot VCG_7$ |

$$P_{200} := P_5 + P_6 + P_7 \qquad VCG_{200} := \frac{P_{200}}{W_2} \qquad VCG_{200} = 15.748 \cdot ft$$

$$W_3 = 339.26 \cdot lton \qquad VCG_8 := .65 \cdot D_{10} \qquad VCG_8 = 24.05 \cdot ft \qquad P_8 := W_3 \cdot VCG_8$$

$$W_{IC} = 49.989 \cdot lton \qquad VCG_9 := D_{10} \qquad VCG_9 = 37 \cdot ft \qquad P_9 := W_{IC} \cdot VCG_9$$

$$W_{CO} = 24.081 \cdot lton \qquad VCG_{10} := 5.6 \cdot ft + .4625 \cdot D_{10} \qquad VCG_{10} = 22.712 \cdot ft \qquad P_{10} := W_{CO} \cdot VCG_{10}$$

$$W_{CC} = 10.027 \cdot lton \qquad VCG_{11} := .5 \cdot D_{10} \qquad VCG_{11} = 18.5 \cdot ft \qquad P_{11} := W_{CC} \cdot VCG_{11}$$

$$W_{498} = 87.9 \cdot lton \qquad VCG_{12} := VCG_{498} \qquad VCG_{12} = -1.2 \cdot ft \qquad P_{12} := W_{498} \cdot VCG_{12}$$

$$W_{AUX} = 612.73 \cdot lton \qquad VCG_{13} := .9 \cdot (D_{10} - 7.4 \cdot ft) \qquad VCG_{13} = 26.64 \cdot ft \qquad P_{13} := W_{AUX} \cdot VCG_{13}$$

$$W_{517} = 4.518 \cdot lton \qquad VCG_{14} := .5 \cdot H_{MB} \qquad VCG_{14} = 18.5 \cdot ft \qquad P_{14} := W_{517} \cdot VCG_{14}$$

$$W_{OFH} = 298.121 \cdot lton \qquad VCG_{15} := .805 \cdot D_{10} \qquad VCG_{15} = 29.785 \cdot ft \qquad P_{15} := W_{OFH} \cdot VCG_{15}$$

$$W_{OFP} = 112.4 \cdot lton \qquad VCG_{16} := 8 \cdot ft + .71 \cdot D_{10} \qquad VCG_{16} = 34.27 \cdot ft \qquad P_{16} := W_{OFP} \cdot VCG_{16}$$

$$ip := 1 .. 16$$

$$P_{WG} := \sum_{ip} P_{ip} + W_P \cdot VCG_P - W_{VP} \cdot VCG_{VP} \qquad P_{WG} = 116221.214 \cdot lton \cdot ft$$

**V!2. Light Ship KG**

$$VCG_{LS} := \frac{P_{WG}}{\sum_{i1} W_{i1}} \qquad VCG_{LS} = 24.363 \cdot ft \qquad KG_{LS} := VCG_{LS} \qquad KG_{LS} = 24.363 \cdot ft$$

**VI3. Calculate Variable Load Weight Group Moments:**

| Weight | VCG | | Product |
|---|---|---|---|
| $W_{F10} = 17.08 \cdot lton$ | $VCG_{17} := .746 \cdot D_{10}$ | $VCG_{17} = 27.602 \cdot ft$ | $P_{17} := W_{F10} \cdot VCG_{17}$ |
| $W_{F31} = 27.121 \cdot lton$ | $VCG_{18} := .55 \cdot D_{10}$ | $VCG_{18} = 20.35 \cdot ft$ | $P_{18} := W_{F31} \cdot VCG_{18}$ |
| $W_{F32} = 6.479 \cdot lton$ | $VCG_{19} := .65 \cdot D_{10}$ | $VCG_{19} = 24.05 \cdot ft$ | $P_{19} := W_{F32} \cdot VCG_{19}$ |
| $W_{F41} = 2321.024 \cdot lton$ | $VCG_{20} := 7.5 \cdot ft$ | $VCG_{20} = 7.5 \cdot ft$ | $P_{20} := W_{F41} \cdot VCG_{20}$ |
| $W_{F42} = 63.8 \cdot lton$ | $VCG_{21} := 10. \cdot ft$ | $VCG_{21} = 10 \cdot ft$ | $P_{21} := W_{F42} \cdot VCG_{21}$ |
| $W_{F46} = 7.2 \cdot lton$ | $VCG_{22} := .35 \cdot D_{10}$ | $VCG_{22} = 12.95 \cdot ft$ | $P_{22} := W_{F46} \cdot VCG_{22}$ |
| $W_{F52} = 22.5 \cdot lton$ | $VCG_{23} := 7.5 \cdot ft$ | $VCG_{23} = 7.5 \cdot ft$ | $P_{23} := W_{F52} \cdot VCG_{23}$ |

$iL := 17..23 \qquad P_{WGL} := \sum_{iL} P_{iL} + W_{VP} \cdot VCG_{VP} \qquad P_{WGL} = 28189.969 \cdot lton \cdot ft$

$W_L := W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10} \qquad W_L = 2687.974 \cdot lton$

$VCG_L := \frac{P_{WGL}}{W_L} \qquad VCG_L = 10.487 \cdot ft$

**VI4. Calculate Ship Stability Characteristics:**

$KG_{MARG} := .5 \cdot ft \quad KG := \frac{W_{LS} \cdot KG_{LS} + W_L \cdot VCG_L}{W_T} + KG_{MARG} \quad C_{IT} := -.497 + 1.44 \cdot C_W \quad C_{IT} = 0.577$

$KB := \frac{T}{3} \cdot \left( 2.5 - \frac{C_P \cdot C_X}{C_W} \right) \qquad BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}} \qquad GM := KB + BM - KG \qquad C_{GMB} := \frac{GM}{B}$

$KG = 20.163 \cdot ft \qquad KB = 11.969 \cdot ft \qquad BM = 13.453 \cdot ft \qquad GM = 5.259 \cdot ft \qquad C_{GMB} = 0.098$ **#ck**

**SUMMARY:**

**ITERATION WEIGHT:** $W_{FL} \equiv 7935 \cdot \text{lton}$

$W_{FL1} = 8087.2 \cdot \text{lton}$ $\quad W_T = 7935.452 \cdot \text{lton}$ $\quad ERR_{WEIGHT} = -0.000057$ $\quad V_{FL} \equiv W_{FL} \cdot 35 \cdot \dfrac{ft^3}{lton}$

**GROSS CHARACTERISTICS:**

$C_P \equiv 0.61$ **(.54 - .64)** $\quad C_{\Delta L} \equiv 63.0 \cdot \dfrac{lton}{ft^3}$ **(45 - 65)** $\quad LWL \equiv 100 \cdot \left(\dfrac{W_{FL}}{C_{\Delta L}}\right)^{\frac{1}{3}}$ $\quad LWL = 501.267 \cdot ft$

$C_X \equiv 0.85$ **(.7 - .85)** $\quad C_V := \dfrac{V_{FL}}{LWL^3}$ $\quad C_V = 0.0022$

$C_{BT} \equiv 2.7$ **(2.8 - 3.7)** $\quad B \equiv \sqrt{\dfrac{C_{BT} \cdot V_{FL}}{C_P \cdot C_X \cdot LWL}}$ $\quad B = 53.713 \cdot ft$ $\quad T = 19.894 \cdot ft$ $\quad C_{LB} = 9.332$ **(7.5 - 10)**

**ENERGY BALANCE:**

$V_S \equiv 28 \cdot knt$ $\quad P_I = 88270 \cdot hp$ $\quad P_{IREQ} = 83960.289 \cdot hp$ $\quad ERR_{POWER} = 0.051$

$V_e \equiv 20 \cdot knt$ $\quad kW_G = 3000 \cdot kW$ $\quad kW_{GREQ} = 2767.538 \cdot kW$ $\quad ERR_{KW} = 0.084$

$E \equiv 7500 \cdot knt \cdot hr$

**AREA/VOLUME BALANCE:**

$V_D \equiv 156000 \cdot ft^3$ $\quad V_T = 836901.666 \cdot ft^3$ $\quad V_{MB} = 72937.95 \cdot ft^3$ $\quad V_{TR} = 559429.982 \cdot ft^3$

$V_{DMIN} = 62976.19 \cdot ft^3$ $\quad V_{HT} = 680901.666 \cdot ft^3$ $\quad V_{AUX} = 87525.54 \cdot ft^3$ $\quad V_{TA} = 563794.306 \cdot ft^3$

$V_{DMAX} = 314880.952 \cdot ft^3$ $\quad V_{TK} = 112643.87 \cdot ft^3$ $\quad ERR_{AREA} = 0.007801$

$D_{10} \equiv 37.0 \cdot ft$ **(Must be > $D_{10MIN}$)**

$D_{10MIN} = 33.418 \cdot ft$

$A_{TR} = 62158.887 \cdot ft^2$ $\quad A_{HR} = 46668.715 \cdot ft^2$ $\quad A_{DR} = 15490.172 \cdot ft^2$

$A_{TA} = 62643.812 \cdot ft^2$ $\quad A_{HA} = 45310.478 \cdot ft^2$ $\quad A_{DA} = 17333.333 \cdot ft^2$

**WEIGHT BALANCE:**

$W_{FL} = 7935 \cdot \text{lton}$ $\quad W_T = 7935.452 \cdot \text{lton}$ $\quad ERR_{WEIGHT} = -0.000057$

$W_1 = 2262.558 \cdot \text{lton}$ $\quad W_5 = 762.975 \cdot \text{lton}$ $\quad W_{LS} = 5247.478 \cdot \text{lton}$

$W_2 = 484.614 \cdot \text{lton}$ $\quad W_6 = 418.261 \cdot \text{lton}$ $\quad W_P = 808.72 \cdot \text{lton}$

$W_3 = 339.26 \cdot \text{lton}$ $\quad W_7 = 154.17 \cdot \text{lton}$ $\quad W_{F41} = 2321.024 \cdot \text{lton}$

$W_4 = 348.597 \cdot \text{lton}$

**STABILITY/PAYLOAD:** $\quad C_{GMB} = 0.098$ **(.09 - .122)** $\quad F_P := \dfrac{W_P}{W_{FL}}$ $\quad F_P = 0.1019$

# SIMPLIFIED COST MODEL

**DD13A**

**Definitions (units):** $\mathrm{Mdol} := \mathrm{coul}$ $\quad \mathrm{Bdol} := 1000 \cdot \mathrm{Mdol}$ $\quad \mathrm{Kdol} := \frac{\mathrm{Mdol}}{1000}$ $\quad \mathrm{dol} := \frac{\mathrm{Kdol}}{1000}$

$\mathrm{lton} := 2240 \cdot \mathrm{lb}$ $\quad \mathrm{hp} := \frac{33000 \cdot \mathrm{ft} \cdot \mathrm{lbf}}{\mathrm{min}}$

## 1. Single Digit Weight Summary:

$i1 := 100, 200 .. 700$

$W_{100} := W_1$ $\quad W_{400} := W_4$ $\quad W_{500} := W_5$ $\quad W_{F_{20}} := W_{F20}$ $\quad W_{F_{20}} = 222.77 \cdot \mathrm{lton}$ #

$W_{200} := W_2$ $\quad W_{IC} = 49.989 \cdot \mathrm{lton}$ $\quad W_{600} := W_6$ $\quad W_{F_{23}} := W_{F23}$ $\quad W_{F_{23}} = 12.73 \cdot \mathrm{lton}$ #

$W_{300} := W_3$ $\quad W_{700} := W_7$ #

**Weight margin:** $W_M := W_{M24}$ $\quad W_M = 477.043 \cdot \mathrm{lton}$ #

## 2. Additional Characteristics:

**Lightship:**

$W_{LS} := \sum_{i1} W_{i1} + W_M$ $\quad W_{LS} = 5247.478 \cdot \mathrm{lton}$

**Costed Military Payload: (helo and helo fuel weight not included)**

$W_{MP} := \left[ \left( W_{400} + W_{700} \right) - W_{IC} \right] + W_{F_{20}} - W_{F_{23}}$ $\quad W_{MP} = 662.818 \cdot \mathrm{lton}$

**Installed Propulsion Power:** $P_I = 88270 \cdot \mathrm{hp}$ $\quad P_{SUM} := P_I$ #

**Manning: (crew + air detachment + staff)**

**Officers:** $N_{C_1} := 15$ **CPO's:** $N_{C_2} := 20$ **Enlisted:** $N_{C_3} := 115$ #

**Ship Service Life:** $L_S := 30$ **Initial Operational Capability:** $Y_{IOC} := 2010$ #

**Total Ship Acquisition:** $N_S := 20$ **Production Rate (per year):** $R_P := 3$ #

## 3. Inflation:

**Base Year:** $Y_B := 2000$ $\quad iy := 1 .. Y_B - 1981$ #

**Average Inflation Rate (%):** $R_I := 3.$ #
**(from 1981)**

$$F_I := \prod_{iy} \left(1 + \frac{R_I}{100}\right) \qquad F_I = 1.754$$

## 4. Lead Ship Cost:

***a. Lead Ship Cost - Shipbuilder Portion:***

**SWBS costs: (See Enclosure 1 for $K_N$ factors); includes escalation estimate**

**Structure** $K_{N1} := \frac{.55 \cdot Mdol}{lton^{.772}}$ $\quad C_{L_{100}} := .03395 \cdot F_I \cdot K_{N1} \cdot (W_{100})^{.772}$ $\quad C_{L_{100}} = 12.731 \cdot Mdol$

**+ Propulsion** $K_{N2} := \frac{1.2 \cdot Mdol}{hp^{.808}}$ $\quad C_{L_{200}} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{SUM}{}^{.808}$ $\quad C_{L_{200}} = 38.799 \cdot Mdol$

**+ Electric** $K_{N3} := \frac{1.0 \cdot Mdol}{lton^{.91}}$ $\quad C_{L_{300}} := .07505 \cdot F_I \cdot K_{N3} \cdot (W_{300})^{.91}$ $\quad C_{L_{300}} = 26.427 \cdot Mdol$

**+ Command, Control, Surveillance**

$K_{N4} := \frac{2.0 \cdot Mdol}{lton^{.617}}$ $\quad C_{L_{400}} := .10857 \cdot F_I \cdot K_{N4} \cdot (W_{400})^{.617}$ $\quad C_{L_{400}} = 14.101 \cdot Mdol$

**(less payload GFM cost)**

**+ Auxiliary** $K_{N5} := \frac{1.5 \cdot Mdol}{lton^{.782}}$ $\quad C_{L_{500}} := .09487 \cdot F_I \cdot K_{N5} \cdot (W_{500})^{.782}$ $\quad C_{L_{500}} = 44.797 \cdot Mdol$

**+ Outfit** $K_{N6} := \frac{1.0 \cdot Mdol}{lton^{.784}}$ $\quad C_{L_{600}} := .09859 \cdot F_I \cdot K_{N6} \cdot (W_{600})^{.784}$ $\quad C_{L_{600}} = 19.632 \cdot Mdol$

**+ Armament** $K_{N7} := \frac{1.0 \cdot Mdol}{lton^{.987}}$ $\quad C_{L_{700}} := .00838 \cdot F_I \cdot K_{N7} \cdot (W_{700})^{.987}$ $\quad C_{L_{700}} = 2.122 \cdot Mdol$

**(Less payload GFM cost)**

**+ Margin Cost:**

$$C_{LM} := \frac{W_M}{(W_{LS} - W_M)} \cdot \left(\sum_{i1} C_{L_{i1}}\right) \qquad C_{LM} = 15.861 \cdot Mdol$$

+ **Integration/Engineering: (Lead ship includes detail design engineering + plans for class)**

$$K_{N8} := \frac{10.\cdot Mdol}{Mdol^{1.099}} \qquad C_{L_{800}} := .034 \cdot K_{N8} \cdot \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{1.099} \qquad C_{L_{800}} = 98.884 \cdot Mdol$$

+ **Ship Assembly + Support: (Lead ship includes all tooling, jigs, special facilities for class)**

$$K_{N9} := \frac{2.0 \cdot Mdol}{(Mdol)^{.839}} \qquad C_{L_{900}} := .135 \cdot K_{N9} \cdot \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{.839} \qquad C_{L_{900}} = 20.519 \cdot Mdol$$

***a. Lead Ship Cost - Shipbuilder Portion (continued):***

= **Total Lead Ship Construction Cost: (BCC):**

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_{800}} + C_{L_{900}} + C_{LM} \qquad C_{LCC} = 293.873 \cdot Mdol$$

+ **Profit:**

$$F_P := .10 \qquad C_{LP} := F_P \cdot C_{LCC} \qquad C_{LP} = 29.387 \cdot Mdol$$ #

= **Lead Ship Price:**

$$P_L := C_{LCC} + C_{LP} \qquad P_L = 323.26 \cdot Mdol$$

+ **Change Orders:**

$$C_{LCORD} := .12 \cdot P_L \qquad C_{LCORD} = 38.791 \cdot Mdol$$ #

= ***Total Shipbuilder Portion:***

$$C_{SB} := P_L + C_{LCORD} \qquad C_{SB} = 362.052 \cdot Mdol$$

## *b. Lead Ship Cost - Government Portion*

**Other support:** $C_{LOTH} := .025 \cdot P_L \qquad C_{LOTH} = 8.082 \cdot Mdol$ #

+ **Program Manager's Growth:** $C_{LPMG} := .1 \cdot P_L \qquad C_{LPMG} = 32.326 \cdot Mdol$ #

+ **Ordnance and Electrical GFE:**
**(Military Payload GFE)**

$$C_{LMPG} := \left(.318 \cdot \frac{Mdol}{lton} \cdot W_{MP} + N_{HELO} \cdot 18.71 \cdot Mdol\right) \cdot F_I$$

$C_{LMPG} = 435.213 \cdot Mdol$ **(or incl actual cost if known)**

+ **HM&E GFE (boats, IC):** $C_{LHMEG} := .02 \cdot P_L$ $C_{LHMEG} = 6.465 \cdot Mdol$

+ **Outfittimg Cost :** $C_{LOUT} := .04 \cdot P_L$ $C_{LOUT} = 12.93 \cdot Mdol$

= ***Total Government Portion:***

$$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT} \qquad C_{LGOV} = 495.016 \cdot Mdol$$

## *c. Total Lead Ship End Cost:* ***(Must always be less than appropriation)***

* ***Total End Cost:*** $C_{LEND} := C_{SB} + C_{LGOV}$ $C_{LEND} = 857.068 \cdot Mdol$

## d. Total Lead Ship Acquisition Cost:

+ **Post-Delivery Cost (PSA):** $C_{LPDEL} := .05 \cdot P_L$ $C_{LPDEL} = 16.163 \cdot Mdol$ #

= **Total Lead Ship Acquisition Cost:** $C_{LA} := C_{LEND} + C_{LPDEL}$ $C_{LA} = 873.231 \cdot Mdo$

## 5. Follow-Ship Cost:

**Learning Rate/Factor:** $R_L := .97$ $F := 2 \cdot R_L - 1$ $F = 0.94$ #

***a. Follow Ship Cost - Shipbuilder Portion***

$$C_{F_{i1}} := F \cdot \frac{C_{L_{i1}}}{coul} \qquad C_{FM} := F \cdot C_{LM} \qquad C_{FM} = 14.909 \cdot Mdol$$

$$C_{F_{800}} := \frac{.104}{Mdol^{1.099}} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{1.099} \qquad C_{F_{800}} \cdot coul = 30.247 \cdot Mdol$$

$$C_{F_{900}} := F \cdot \frac{C_{L_{900}}}{coul} \qquad C_{F_{900}} = 19.288$$

| $\frac{C_{F_{i1}} \cdot coul}{Mdol}$ |
|---|
| 11.967 |
| 36.471 |
| 24.841 |
| 13.255 |
| 42.109 |
| 18.454 |
| 1.995 |

**Total Follow Ship Construction Cost: (BCC)**

$$C_{FCC} := \sum_{i1} \frac{C_{F_{i1}} \cdot Mdol}{coul} + \frac{C_{F_{800}} \cdot coul}{Mdol} + C_{F_{900}} + \frac{C_{FM}}{Mdol} \qquad C_{FCC} \cdot coul = 213.536 \, Mdol$$

**+ Profit:**

$F_P := .1 \qquad C_{FP} := F_P \cdot C_{FCC} \cdot coul \qquad C_{FP} = 21.354 \, Mdol$ #

= **Follow Ship Price:**

$P_F := C_{FCC} \cdot coul + C_{FP} \qquad P_F = 234.89 \, Mdol$

**+ Change Orders:**

$C_{FCORD} := .08 \cdot P_L \qquad C_{FCORD} = 25.861 \, Mdol$ #

= **Total Follow Ship Shipbuilder Portion:**

$C_{FSB} := P_F + C_{FCORD} \qquad C_{FSB} = 260.751 \, Mdol$

## *b. Follow Ship Cost - Government Portion*

**Other support:** $C_{FOTH} := .025 \cdot P_F \qquad C_{FOTH} = 5.872 \, Mdol$ #

**+ Program Manager's Growth:** $C_{FPMG} := .05 \cdot P_F$ #

**number of helo's:** $N_{HELO} = 2$

**+ Ordnance and Electrical GFE:**
**(Military Payload GFE)**

$$C_{FMPG} := \left( .3 \cdot \frac{Mdol}{lton} \cdot W_{MP} + 18.710 \cdot Mdol \cdot N_{HELO} \right) \cdot F_I$$

$C_{FMPG} = 414.293 \, Mdol$

**+ HM&E GFE (boats, IC):** $C_{FHMEG} := .02 \cdot P_F \qquad C_{FHMEG} = 4.698 \, Mdol$ #

**+ Outfittimg Cost:** $C_{FOUT} := .04 \cdot P_F \qquad C_{FOUT} = 9.396 \, Mdol$ #

= ***Total Follow Ship Government Cost:***

$$C_{FGOV} := C_{FOTH} + C_{FPMG} + C_{FMPG} + C_{FHMEG} + C_{FOUT} \qquad C_{FGOV} = 446.003 \, Mdol$$

## c. Total Follow Ship End Cost:
## (Must always be less than SCN appropriation)

* ***Total Follow Ship End Cost:***

$C_{FEND} := C_{FSB} + C_{FGOV}$ $\qquad$ $C_{FEND} = 706.754 \cdot \text{Mdol}$

## d. Total Follow Ship Acquisition Cost:

**+ Post-Delivery Cost (PSA):** $\quad C_{FPDEL} := .05 \cdot P_F \qquad C_{FPDEL} = 11.744 \cdot \text{Mdol}$ #

= ***Total Follow Ship Acquisition Cost:*** $\quad C_{FA} := C_{FEND} + C_{FPDEL} \qquad C_{FA} = 718.498 \cdot \text{Mdol}$

## AVERAGE SHIP ACQUISITION COST:

$$C_{AV} := \frac{\frac{C_{FA} - C_{FMPG}}{F} \cdot (N_S - 1)^{\frac{\ln(2 \cdot R_L)}{\ln(2)}} + (N_S - 1) \cdot C_{FMPG} + C_{LA}}{N_S} \qquad C_{AV} = 707.368 \cdot \text{Mdol}$$

## 6. Life Cycle Cost:

***a. Research and development***

**Ship design and development:**

$$C_{SDD} := 1.1 \cdot \left( .571 \cdot \frac{C_{FSB}}{F} + .072 \cdot C_{LMPG} \right) \qquad C_{SDD} = 208.7 \cdot \text{Mdol}$$ #

**+ Ship test and evaluation**

$$C_{STE} := 1.2 \cdot \left( .499 \cdot \frac{C_{FSB}}{F} + .647 \cdot C_{LMPG} \right) \qquad C_{STE} = 504.003 \cdot \text{Mdol}$$ #

= ***Total Ship R&D Cost:***

$C_{RD} := C_{SDD} + C_{STE} \qquad C_{RD} = 712.704 \cdot \text{Mdol}$

***b) Investment (less base facilities, unrep, etc)***

**Ships:**

$$C_{SPE} := \frac{C_{FA}}{F} \cdot N_S^{\frac{\ln(2 \cdot R_L)}{\ln(2)}} \qquad C_{SPE} = 13.402 \cdot \text{Bdol}$$

**average ship cost:** $C_{AVG} := \frac{C_{SPE}}{N_S}$ $C_{AVG} = 670.079 \cdot Mdol$

**+ Support Equipment (shore-based)**

**ship:** $C_{SSE} := .15 \cdot C_{SPE}$ $C_{SSE} = 2.01 \cdot Bdol$ #

**+ Spares and repair parts (shore supply)**

**ship:** $C_{ISS} := .1 \cdot C_{SPE}$ $C_{ISS} = 1.34 \cdot Bdol$ #

**= <u>Total Investment Cost</u>:** $C_{INV} := C_{SPE} + C_{SSE} + C_{ISS}$ $C_{INV} = 16.752 \cdot Bdol$

## *c) Operations and Support*

**Personnel (Pay and Allowances)**

$$C_{PAY} := F_I \cdot \left[.026184 \cdot N_{C_1} + .01151 \cdot \left(N_{C_2} + N_{C_3}\right)\right] \cdot N_S \cdot L_S \cdot Mdol \qquad C_{PAY} = 2.048 \cdot Bdol$$

$$C_{TAD} := F_I \cdot \left(N_{C_1} + N_{C_2} + N_{C_3}\right) \cdot N_S \cdot L_S \cdot 2.6 \cdot 10^{-6} \cdot Mdol \qquad C_{TAD} = 0.41 \cdot Mdol$$

$$C_{PERS} := C_{PAY} + C_{TAD} \qquad C_{PERS} = 2.048 \cdot Bdol$$

**+ Operations:**

**Operating hours/year:** $H := 2500 \cdot hr$ #

$$C_{OPS} := N_S \cdot L_S \cdot \left[F_I \cdot Kdol \cdot \left[188. + 2.232 \cdot \left(N_{C_1} + N_{C_2} + N_{C_3}\right) - \frac{H}{26.9 \cdot hr}\right] + \frac{C_{AVG}}{769.2} + \frac{C_{FMPG}}{196}\right]$$

$$C_{OPS} = 2.243 \cdot Bdol$$

**+ Maintenance**

$$C_{MTC} := N_S \cdot L_S \cdot \left[F_I \cdot Kdol \cdot \left[2967 + 4.814 \cdot \left(N_{C_1} + N_{C_2} + N_{C_3}\right) - \frac{H}{3.05 \cdot hr}\right] + \frac{C_{AVG}}{156.25}\right]$$

$$C_{MTC} = 5.592 \cdot Bdol$$

**+ Energy (Assumes all operation at Endurance Power with no electric load)**

**Fuel Rate:** $FR \cdot P_{eBAVG} = 4.747 \cdot \frac{lton}{hr}$ $C_{FUEL} := .9 \cdot \frac{dol}{gal}$ #

$$C_{EGY} := N_S \cdot L_S \cdot C_{FUEL} \cdot \frac{H}{6.8 \cdot \frac{lb}{gal}} \cdot FR \cdot P_{eBAVG} \qquad C_{EGY} = 2.111 \cdot Bdol$$

**+ Replenishment Spares**

$$C_{REP} := C_{ISS} \cdot \frac{L_S - 4}{4} \qquad C_{REP} = 8.711 \cdot Bdol$$

**+ Major Support (COH, ROH):**

$$C_{MSP} := N_S \cdot L_S \cdot \left[ 698. + 5.988 \cdot \left( N_{C_1} + N_{C_2} + N_{C_3} \right) - \frac{H}{10.36 \cdot hr} \right] \cdot Kdol \cdot F_I + .0022 \cdot C_{AVG}$$

$$C_{MSP} = 1.427 \cdot Bdol$$

= ***Total Operation and Support Cost:*** $C_{OAS} := C_{PERS} + C_{OPS} + C_{MTC} + C_{EGY} + C_{REP} + C_{MSP}$

$$C_{OAS} = 22.133 \cdot Bdol$$

## d. Residual Value:

$$RES := .5 \cdot C_{SPE} \cdot \left( 1 - \frac{2}{L_S} \right)^{L_S} \qquad RES = 0.846 \cdot Bdol$$

## e. Total Program

* ***Total Life Cycle Cost (Undiscounted):*** $C_{LIFE} := C_{RD} + C_{INV} + C_{OAS} - RES \qquad C_{LIFE} = 38.752 \cdot Bdol$

# 7. Discounted Life Cycle Cost:

**Discount Rate:** $R_D := .1$ #

***a. Discounted R&D:*** **Length of R&D Phase:** $L_{RD} := 13$ #

**end:** $E_{RD} := Y_{IOC} + 2 - Y_B \qquad E_{RD} = 12$ **(normalized to base year)**

**start:** $B_{RD} := E_{RD} - L_{RD} + 1 \qquad B_{RD} = 0$

$$F_{DRD} := \frac{\sum_{y = B_{RD}}^{E_{RD}} \frac{1}{(1 + R_D)^y}}{L_{RD}} \qquad F_{DRD} = 0.601$$

$$C_{DRD} := F_{DRD} \cdot C_{RD} \qquad C_{DRD} = 428.373 \cdot Mdol$$

*b. Discounted Investment:*

**start:** $B_{INV} := E_{RD} + 1$

**end:** $E_{INV} := B_{INV} + \text{ceil}\left(\left(\frac{N_S - 1}{R_P}\right)\right) \qquad E_{INV} = 20$

$$L_{INV} := E_{INV} - B_{INV} + 1 \qquad L_{INV} = 8$$

$$F_{DINV} := \frac{\sum_{y = B_{INV}}^{E_{INV}} \frac{1}{(1 + R_D)^y}}{L_{INV}} \qquad F_{DINV} = 0.212$$

$$C_{DINV} := F_{DINV} \cdot C_{INV} \qquad C_{DINV} = 3.56 \cdot Bdol$$

*c. Discounted O&S:*

**start:** $B_{OAS} := E_{INV} + 1 \qquad B_{OAS} = 21$

**end:** $E_{OAS} := B_{OAS} + L_S - 1 \qquad E_{OAS} = 50$

$$L_{OAS} := E_{OAS} - B_{OAS} + 1 \qquad L_{OAS} = 30$$

$$F_{DOAS} := \frac{\sum_{y = B_{OAS}}^{E_{OAS}} \frac{1}{(1 + R_D)^y}}{L_{OAS}} \qquad F_{DOAS} = 0.047$$

$$C_{DOAS} := F_{DOAS} \cdot C_{OAS} \qquad C_{DOAS} = 1.034 \cdot Bdol$$

### *d. Discounted Residual Value:*

$$RES_D := RES \cdot \left(\frac{1}{1 + R_D}\right)^{E_{OAS}+1} \qquad RES_D = 6.549 \cdot Mdol$$

### *e. Total Discounted Life Cycle Cost:*

$$C_{DLIFE} := C_{DRD} + C_{DINV} + C_{DOAS} - RES_D \qquad C_{DLIFE} = 5.015 \cdot Bdol$$

# Appendix B

# Design Decomposition

**FR/DP Table**

**Index:**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | | | |
| *1* | | Move through water | Propulsion system | |
| *2* | | Maintain desired course | Maneuvering and control system | |
| *3* | | Neutralize enemy targets | Combat systems configuration | |
| *4* | | Protect from enemy attack | Countermeasures methods | |
| *5* | | Conduct sustained underway operations | Support / Auxiliary systems | |
| *6* | | Operate on surface of water | Hull form | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O |
| ***FR.#.2*** | x | X | O | O | O | O |
| ***FR.#.3*** | O | O | X | O | O | O |
| ***FR.#.4*** | O | O | X | X | O | O |
| ***FR.#.5*** | X | O | O | O | X | O |
| ***FR.#.6*** | X | X | X | X | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Uneven hydrodynamic forces from single screw Engine combinations affect twin screw ship maneuvering |
| *5* | *1* | Fuel consumption determines endurance range |
| *5* | *6* | Fuel consumption determines endurance range |
| *6* | *1* | Component of total ship weight |
| *6* | *2* | Component of total ship weight |
| *6* | *3* | Component of total ship weight |
| *6* | *4* | Component of total ship weight |
| *6* | *5* | Component of total ship weight |

**Related Constraints**

| No. | Parent | Keyword | Description | Comment | 1 | 2 | 3 | 4 | 5 | 6 | Verification |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | Initial acquisition cost < $ XX M | | * | * | * | * | * | * | |
| 2 | | | Average hourly operating cost < $ XX | | * | * | * | * | * | * | |
| 3 | | | Full load displacement = Total weight | | | | | | | * | |
| 4 | | | Ensure intact stability (GM > 0 ft) | | | | | | | * | |
| 5 | | | Ensure acceptable transverse dynamic stability (0.09 < GM/B < 0.122) | | | | | | | * | |
| 6 | | | Installed propulsive power > Required propulsive power | | * | | | | | * | |
| 7 | | | Installed electrical power > Required electrical power | | | | | | * | | |
| 8 | | | Total available volume > Total required volume | | | | | * | | * | |
| 9 | | | Total available arrangeable area > Total required arrangeable area | | | | | * | | * | |
| 10 | | | Incorporate design growth margins (weight, KG, propulsion and electrical power) | | * | | | | * | * | |
| 11 | | | Always operate at DWL | | | | | | | * | |
| 12 | | | Carry adequate fuel to transit endurance range at endurance speed | | * | | | | * | * | |

**FR/DP Table**

**Index:**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | | | |
| *1* | | Move through water | Propulsion system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Move through water | Propulsion system | |
| *1* | | Produce propulsive power to achieve sustained speed | Main propulsion engines (MPE) | |
| *2* | | Provide propulsive power at usable speed (rpm) | Reduction gear | |
| *3* | | Transfer power to water | CRP propeller | |
| *4* | | Control speed and direction of movement locally | Engineering operations station (EOS) | |
| *5* | | Control speed and direction of movement remotely | Lee helm | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Must use legacy engines and "project" propulsive power req'd to overcome hull resistance |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | X | X | O | O | O |
| ***FR.#.3*** | O | X | X | O | O |
| ***FR.#.4*** | X | O | X | X | O |
| ***FR.#.5*** | X | O | X | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Engine speed (rpm's) affects required reduction ratio |
| *4* | *1* | Propulsion engines are one component of controlling movement |
| *4* | *3* | Propulsion engines are one component of controlling movement |
| *5* | *1* | Propulsion engines are one component of controlling movement |
| *5* | *3* | Propulsion engines are one component of controlling movement |
| *5* | *4* | Propulsion engines are one component of controlling movement |

**FR/DP Table**

**Index: 1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Produce propulsive power to achieve sustained speed | Main propulsion engines (MPE) | |
| *1* | | Provide inertia to start engine | Starting air system | |
| *2* | | Provide fuel for continuous engine operation | MPE fuel system | |
| *3* | | Cool engine | MPE lube oil system | |
| *4* | | Provide air to support engine combustion | Engine inlet ducting | |
| *5* | | Remove combustion products | Engine exhaust ducting | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | O | X | O | O |
| ***FR.#.4*** | O | O | O | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**Related Constraints**

| *No.* | *Parent* | *Keyword* | *Description* | *Comment* | *1* | *2* | *3* | *4* | *5* | *Verification* |
|---|---|---|---|---|---|---|---|---|---|---|
| *1* | | | Fuel supply rate must support combined engine specific fuel comsumption (sfc) | Constraint vs FR added because engines already set at higher level. Selected engines have associated sfc which does not change. | | * | | | | |

**FR/DP Table**

**Index: 1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide inertia to start engine | Starting air system | |
| *1* | | Increase air pressure to required pressure | Air compressor | |
| *2* | | Hold air at required pressure | Air flasks | |
| *3* | | Start /stop air flow | Valves | |
| *4* | | Transport air to flask / engine | Air piping | |
| *5* | | Determine air pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | X | O | X | O | O |
| *FR.#.4* | X | O | X | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Require pressure differential to cause air flow |
| *4* | *1* | Require pressure differential to cause air flow (transport) |
| *4* | *3* | Require pressure differential to cause air flow (transport) |

**FR/DP Table**

**Index: 1.1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Increase air pressure to required pressure | Air compressor | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 1.1.1.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Energize / de-energize | Control panel | |
| *1* | | Actuate / terminate system operation | Electrical switch | |
| *2* | | Read system voltage and current | Internal volt/amp-meter | |
| *3* | | Determine if electrical parameters are within specification | Programmed electrical database | |
| *4* | | Respond to correct potential casualty | Electrical casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | X | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 1.1.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Start /stop air flow | Valves | |
| *1* | | Open / close valves | Electrical relay | |
| *2* | | Verify valve alignment | Sensors | |
| *3* | | Report valve alignment | Display panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 1.1.1.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine air pressure | Pressure gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Provide fuel for continuous engine operation | MPE fuel system | |
| *1* | | Receive fuel from fuel transfer system | Piping connection | |
| *2* | | Supply fuel | Engine fuel pump | |
| *3* | | Start / stop fuel flow | Valves | |
| *4* | | Transport fuel to engine | Engine fuel piping | |
| *5* | | Determine fuel pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | X | X | O | O |
| ***FR.#.4*** | O | X | X | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**FR/DP Table**

**Index: 1.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Supply fuel | Engine fuel pump | |
| *1* | | Activate / de-activate pump | Engine rotation | |
| *2* | | Control fuel output | Engine rotation speed | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Speed is characteristic of rotation |

**FR/DP Table**

**Index: 1.1.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Start / stop fuel flow | Valves | |
| *1* | | Open / close valves | Electrical relay | |
| *2* | | Verify valve alignment | Sensors | |
| *3* | | Report valve alignment | Display panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 1.1.2.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine fuel pressure | Pressure gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 |
|---|---|---|---|---|---|
| FR.#.1 | X | O | O | O | O |
| FR.#.2 | X | X | O | O | O |
| FR.#.3 | X | X | X | O | O |
| FR.#.4 | X | O | O | X | O |
| FR.#.5 | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| 2 | 1 | Reading sensed for recording |
| 3 | 1 | Reading sensed before reported |
| 3 | 2 | Reading sensed before reported |
| 4 | 1 | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Cool engine | MPE lube oil system | |
| 1 | | Hold lube oil | MPE lube oil sumps | |
| 2 | | Supply / remove lube oil | Pumps | |
| 3 | | Start / stop lube oil flow | Valves | |
| 4 | | Transport lube oil | MPE lube oil piping | |
| 5 | | Determine lube oil quantity | Gages measuring sump level / Sight glasses | |
| 6 | | Determine lube oil pressure | Pressure gages | |
| 7 | | Determine lube oil temperature | Temperature gages | |
| 8 | | Cool lube oil | Sea water system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* |
|---|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O | O |
| *FR.#.5* | O | O | O | O | X | O | O | O |
| *FR.#.6* | O | O | O | O | O | X | O | O |
| *FR.#.7* | O | O | O | O | O | O | X | O |
| *FR.#.8* | O | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 1.1.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove lube oil | Pumps | |
| *1* | | Activate / de-activate pumps | Engine rotation | |
| *2* | | Control lube oil output | Engine rotation speed | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Speed is characteristic of rotation |

**FR/DP Table**

**Index: 1.1.3.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Start / stop lube oil flow | Valves | |
| *1* | | Open / close valves | Electrical relay | |
| *2* | | Verify valve alignment | Sensors | |
| *3* | | Report valve alignment | Display panel | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 |
|---|---|---|---|
| FR.#.1 | X | O | O |
| FR.#.2 | O | X | O |
| FR.#.3 | O | X | X |

**FR/DP Table**

**Index: 1.1.3.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Determine lube oil quantity | Gages measuring sump level / Sight glasses | |
| 1 | | Read gages | Sensors | |
| 2 | | Record gage reading | Memory bank | |
| 3 | | Report gage reading | Display panel | |
| 4 | | Determine if reading is within specifications | Programmed database | |
| 5 | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 |
|---|---|---|---|---|---|
| FR.#.1 | X | O | O | O | O |
| FR.#.2 | X | X | O | O | O |
| FR.#.3 | X | X | X | O | O |
| FR.#.4 | X | O | O | X | O |
| FR.#.5 | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| 2 | 1 | Reading sensed for recording |
| 3 | 1 | Reading sensed before reported |
| 3 | 2 | Reading sensed before reported |
| 4 | 1 | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.1.3.6**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine lube oil pressure | Pressure gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.1.3.7**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine lube oil temperature | Temperature gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | X | X | O | O | O |
| ***FR.#.3*** | X | X | X | O | O |
| ***FR.#.4*** | X | O | O | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.1.3.8**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Cool lube oil | Sea water system | |
| *1* | | Receive / discharge cooling water from / to sea | Hull openings | |
| *2* | | Supply / remove sea water | Pumps | |
| *3* | | Start / stop sea water flow | Valves | |
| *4* | | Transport sea water | Sea water piping | |
| *5* | | Determine sea water pressure | Pressure gages | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | X | X | O | O |
| ***FR.#.4*** | O | X | X | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**FR/DP Table**

**Index: 1.1.3.8.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove sea water | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 1.1.3.8.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Energize / de-energize | Control panel | |
| *1* | | Actuate / terminate system operation | Electrical switch | |
| *2* | | Read system voltage and current | Internal volt/amp-meter | |
| *3* | | Determine if electrical parameters are within specification | Programmed electrical database | |
| *4* | | Respond to correct potential casualty | Electrical casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | X | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 1.1.3.8.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Start / stop sea water flow | Valves | |
| *1* | | Open / close valves | Electrical relay | |
| *2* | | Verify valve alignment | Sensors | |
| *3* | | Report valve alignment | Display panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 1.1.3.8.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine sea water pressure | Pressure gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide propulsive power at usable speed (rpm) | Reduction gear | |
| *1* | | Connect to engine | Clutch | |
| *2* | | Cool reduction gear | Lube oil system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 1.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Connect to engine | Clutch | |
| *1* | | Activate / de-activate clutch | Clutch air system | |
| *2* | | Engage engine shaft | Rubber boot | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need air pressure to engage |

**FR/DP Table**

**Index: 1.2.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Activate / de-activate clutch | Clutch air system | |
| *1* | | Receive air from MPE starting air system | Piping connection | |
| *2* | | Start /stop air flow | Valves | |
| *3* | | Transport air to flask / clutch | Air piping | |
| *4* | | Determine air pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | X | X | O | O |
| *FR.#.3* | X | X | X | O |
| *FR.#.4* | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Piping connection provides air required o start flow |
| *3* | *1* | Must have air via piping connection to transport |
| *3* | *2* | Must have air via piping connection to transport |

**FR/DP Table**

**Index: 1.2.1.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Start /stop air flow | Valves | |
| *1* | | Open / close valves | Electrical relay | |
| *2* | | Verify valve alignment | Sensors | |
| *3* | | Report valve alignment | Display panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 1.2.1.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine air pressure | Pressure gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Cool reduction gear | Lube oil system | |
| *1* | | Hold lube oil | Lube oil sump | |
| *2* | | Supply / remove lube oil (reduction gear not turning) | Lube oil standby pumps | |
| *3* | | Supply / remove lube oil (reduction gear turning) | Pumps | |
| *4* | | Start / stop lube oil flow | Valves | |
| *5* | | Transport lube oil | Lube oil piping | |
| *6* | | Determine lube oil quantity | Gages measuring sump level / sight glasses | |
| *7* | | Determine lube oil pressure | Pressure gages | |
| *8* | | Determine lube oil temperature | Temperature gages | |
| *9* | | Cool lube oil | Sea water system | |
| *10* | | Ensure lube oil free of sediment | Purifier | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* | *DP.#.9* | *DP.#.10* |
|---|---|---|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O | O | O | O |
| *FR.#.5* | O | X | X | X | X | O | O | O | O | O |
| *FR.#.6* | O | O | O | O | O | X | O | O | O | O |
| *FR.#.7* | O | O | O | O | O | O | X | O | O | O |
| *FR.#.8* | O | O | O | O | O | O | O | X | O | O |
| *FR.#.9* | O | O | O | O | O | O | O | O | X | O |
| *FR.#.10* | O | O | O | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 1.2.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove lube oil (reduction gear not turning) | Lube oil standby pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Recieve signal to energize / de-energize through hardwire connection point |

**FR/DP Table**

**Index: 1.2.2.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Energize / de-energize | Control panel | |
| *1* | | Actuate / terminate system operation | Electrical switch | |
| *2* | | Read system voltage and current | Internal volt/amp-meter | |
| *3* | | Determine if electrical parameters are within specification | Programmed electrical database | |
| *4* | | Respond to correct potential casualty | Electrical casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | X | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 1.2.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove lube oil (reduction gear turning) | Pumps | |
| *1* | | Activate / de-activate pumps | Reduction gear rotation | |
| *2* | | Control lube oil output | Reduction gear rotation speed | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Speed is characteristic of rotation |

**FR/DP Table**

**Index: 1.2.2.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Start / stop lube oil flow | Valves | |
| *1* | | Open / close valves | Electrical relay | |
| *2* | | Verify valve alignment | Sensors | |
| *3* | | Report valve alignment | Display panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 1.2.2.6**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine lube oil quantity | Gages measuring sump level / sight glasses | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.2.2.7**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine lube oil pressure | Pressure gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| 2 | 1 | Reading sensed for recording |
| 3 | 1 | Reading sensed before reported |
| 3 | 2 | Reading sensed before reported |
| 4 | 1 | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.2.2.8**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine lube oil temperature | Temperature gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| 2 | 1 | Reading sensed for recording |
| 3 | 1 | Reading sensed before reported |
| 3 | 2 | Reading sensed before reported |
| 4 | 1 | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.2.2.9**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Cool lube oil | Sea water system | |
| *1* | | Receive / discharge cooling water from / to sea | Hull openings | |
| *2* | | Supply / remove sea water | Pumps | |
| *3* | | Start / stop sea water flow | Valves | |
| *4* | | Transport sea water | Sea water piping | |
| *5* | | Determine sea water pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | X | X | O | O |
| ***FR.#.4*** | O | X | X | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**FR/DP Table**

**Index: 1.2.2.9.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove sea water | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 1.2.2.9.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Energize / de-energize | Control panel | |
| *1* | | Actuate / terminate system operation | Electrical switch | |
| *2* | | Read system voltage and current | Internal volt/amp-meter | |
| *3* | | Determine if electrical parameters are within specification | Programmed electrical database | |
| *4* | | Respond to correct potential casualty | Electrical casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | X | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 1.2.2.9.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Start / stop sea water flow | Valves | |
| *1* | | Open / close valves | Electrical relay | |
| *2* | | Verify valve alignment | Sensors | |
| *3* | | Report valve alignment | Display panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 1.2.2.9.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine sea water pressure | Pressure gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.2.2.10**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Ensure lube oil free of sediment | Purifier | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 1.2.2.10.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Energize / de-energize | Control panel | |
| *1* | | Actuate / terminate system operation | Electrical switch | |
| *2* | | Read system voltage and current | Internal volt/amp-meter | |
| *3* | | Determine if electrical parameters are within specification | Programmed electrical database | |
| *4* | | Respond to correct potential casualty | Electrical casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | X | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Transfer power to water | CRP propeller | |
| *1* | | Receive speed (rpm) input from reduction gear | Shaft | |
| *2* | | Control thrust direction (fore / aft) | Blade pitch angle | |
| *3* | | Produce thrust | Propeller blades (number and area) | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 1.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Control thrust direction (fore / aft) | Blade pitch angle | |
| *1* | | Allow pitch angle variation | Pivotal blade connection at hub | |
| *2* | | Control pitch angle | Controllable pitch propeller (CPP) hydraulic system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | x | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Sets angle limits |

**FR/DP Table**

**Index: 1.3.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Control pitch angle | Controllable pitch propeller (CPP) hydraulic system | |
| *1* | | Hold hydraulic oil | Hydraulic oil sump | |
| *2* | | Supply / return hydraulic oil | Pumps | |
| *3* | | Start / stop hydraulic oil flow | Valves | |
| *4* | | Direct hydraulic oil flow | Solenoid valves | |
| *5* | | Transport hydraulic oil to propeller / sump | Hydraulic oil piping | |
| *6* | | Determine hydraulic oil quantity | Gages measuring hydraulic oil level / Sight glasses | |
| *7* | | Determine hydraulic oil pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O |
| *FR.#.5* | O | X | X | O | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 1.3.2.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / return hydraulic oil | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 1.3.2.2.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Energize / de-energize | Control panel | |
| *1* | | Actuate / terminate system operation | Electrical switch | |
| *2* | | Read system voltage and current | Internal volt/amp-meter | |
| *3* | | Determine if electrical parameters are within specification | Programmed electrical database | |
| *4* | | Respond to correct potential casualty | Electrical casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | X | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 1.3.2.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Start / stop hydraulic oil flow | Valves | |
| *1* | | Open / close valves | Electrical relay | |
| *2* | | Verify valve alignment | Sensors | |
| *3* | | Report valve alignment | Display panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 1.3.2.2.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Direct hydraulic oil flow | Solenoid valves | |
| ***1*** | | Receive electrical power | Electrical hardwire connection point | |
| ***2*** | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | ***DP.#.1*** | ***DP.#.2*** |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| ***2*** | ***1*** | Must receive electrical power to energize |

**FR/DP Table**

**Index: 1.3.2.2.4.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Energize / de-energize | Control panel | |
| ***1*** | | Actuate / terminate system operation | Electrical switch | |
| ***2*** | | Read system voltage and current | Internal volt/amp-meter | |
| ***3*** | | Determine if electrical parameters are within specification | Programmed electrical database | |
| ***4*** | | Respond to correct potential casualty | Electrical casualty control protocol | |

**Total Design Matrix Information**

| | ***DP.#.1*** | ***DP.#.2*** | ***DP.#.3*** | ***DP.#.4*** |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | O | X | O | O |
| ***FR.#.3*** | O | X | X | O |
| ***FR.#.4*** | O | O | X | X |

**FR/DP Table**

**Index: 1.3.2.2.6**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine hydraulic oil quantity | Gages measuring hydraulic oil level / Sight glasses | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.3.2.2.7**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine hydraulic oil pressure | Pressure gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Control speed and direction of movement locally | Engineering operations station (EOS) | |
| *1* | | Input desired speed and direction of movement | Throttle control | |
| *2* | | Display operator input | Indicator gage | |
| *3* | | Produce desired engine speed / propeller pitch combination | Propulsion control air system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | x | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Throttle control may not produce desired result due to calibration problem |

**FR/DP Table**

**Index: 1.4.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Input desired speed and direction of movement | Throttle control | |
| *1* | | Receive propulsion order | CPO GSM | |
| *2* | | Implement propulsion order | CPO GSM | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Same pers receives and implements order |

**FR/DP Table**

**Index: 1.4.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Display operator input | Indicator gage | |
| *1* | | Read indicator gage | CPO GSM | |
| *2* | | Verify proper pressure corresponding to order | CPO GSM | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Same pers reads and verifies gage |

**FR/DP Table**

**Index: 1.4.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Produce desired engine speed / propeller pitch combination | Propulsion control air system | |
| *1* | | Increase air pressure to required pressure | Air compressor | |
| *2* | | Hold air at required pressure | Air flasks | |
| *3* | | Start /stop air flow | Valves | |
| *4* | | Transport air to flask / engine, propeller control | Air piping | |
| *5* | | Determine air pressure | Pressure gages | |
| *6* | | Transfer control between local / remote stations | Transfer valve | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *6* | | Valve directs flow to either EOS or lee helm |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O | O |
| ***FR.#.3*** | X | O | X | O | O | O |
| ***FR.#.4*** | X | O | X | X | O | O |
| ***FR.#.5*** | O | O | O | O | X | O |
| ***FR.#.6*** | O | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Require pressure differential to cause air flow |
| *4* | *1* | Require pressure differential to cause air flow (transport) |
| *4* | *3* | Require pressure differential to cause air flow (transport) |

**FR/DP Table**

**Index: 1.4.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Increase air pressure to required pressure | Air compressor | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 1.4.3.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Energize / de-energize | Control panel | |
| *1* | | Actuate / terminate system operation | Electrical switch | |
| *2* | | Read system voltage and current | Internal volt/amp-meter | |
| *3* | | Determine if electrical parameters are within specification | Programmed electrical database | |
| *4* | | Respond to correct potential casualty | Electrical casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | X | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 1.4.3.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Start /stop air flow | Valves | |
| *1* | | Open / close valves | Electrical relay | |
| *2* | | Verify valve alignment | Sensors | |
| *3* | | Report valve alignment | Display panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 1.4.3.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine air pressure | Pressure gages | |
| *1* | | Read gages | Sensors | |
| *2* | | Record gage reading | Memory bank | |
| *3* | | Report gage reading | Display panel | |
| *4* | | Determine if reading is within specifications | Programmed database | |
| *5* | | Respond to correct potential casualty | Casualty control protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | X | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Reading sensed for recording |
| *3* | *1* | Reading sensed before reported |
| *3* | *2* | Reading sensed before reported |
| *4* | *1* | Reading sensed and compared to database values |

**FR/DP Table**

**Index: 1.4.3.6**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Transfer control between local / remote stations | Transfer valve | |
| *1* | | Position valve to achieve local/remote control | CPO GSM | |
| *2* | | Verify control received by proper station | CPO GSM | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Same pers transfers and verifies control |

**FR/DP Table**

**Index: 1.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Control speed and direction of movement remotely | Lee helm | |
| ***1*** | | Input desired speed and direction of movement | Throttle control | |
| ***2*** | | Display operator input | Indicator gage | |
| ***3*** | | Produce desired engine speed / propeller pitch combination | Propulsion control air system | |

**Total Design Matrix Information**

| | ***DP.#.1*** | ***DP.#.2*** | ***DP.#.3*** |
|---|---|---|---|
| ***FR.#.1*** | X | O | O |
| ***FR.#.2*** | O | X | O |
| ***FR.#.3*** | x | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| ***3*** | ***1*** | Throttle control may not produced desired result due to calibration problem |

**FR/DP Table**

**Index:**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | | | |
| *2* | | Maintain desired course | Maneuvering and control system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Maintain desired course | Maneuvering and control system | |
| *1* | | Determine if course is "safe" | Navigation equipment | |
| *2* | | Alter existing course | Rudder | |
| *3* | | Maneuver alongside pier | Bow thrusters / APU's | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Use standard legacy systems. Therefore each system is not decomposed in detail. |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine if course is "safe" | Navigation equipment | |
| *1* | | Provide worldwide position reference frame | Inertial gyroscope | |
| *2* | | Determine position | Global positioning system (GPS) | |
| *3* | | Determine distance to land / surface contacts | Navigation radar | |
| *4* | | Determine water depth | Fathometer | |
| *5* | | Determine speed | Pitsword | |
| *6* | | Record position and contact positions | Chart | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *4* | | Standard sonar-type fathometer |
| *5* | | Standard salinity cell-type pitsword |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O |
| *FR.#.3* | X | O | X | O | O | O |
| *FR.#.4* | O | O | O | X | O | O |
| *FR.#.5* | X | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Requires gyro input for actual vs. relative readings |
| *5* | *1* | Requires gyro input |

**FR/DP Table**

**Index: 2.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide worldwide position reference frame | Inertial gyroscope | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Require electrical hardwire to energize |

**FR/DP Table**

**Index: 2.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine position | Global positioning system (GPS) | |
| *1* | | Receive satellite signal | Antenna | |
| *2* | | Display ship's position (latitude and longitude) | GPS information screen | |
| *3* | | Receive electrical power | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | O | X | O | O |
| ***FR.#.3*** | O | O | X | O |
| ***FR.#.4*** | O | O | X | X |

**FR/DP Table**

**Index: 2.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine distance to land / surface contacts | Navigation radar | |
| *1* | | Display position of contacts | Radar repeater | |
| *2* | | Receive electrical power | Electrical hardwire connection point | |
| *3* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 2.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine water depth | Fathometer | |
| *1* | | Display water depth | Fathometer information screen | |
| *2* | | Receive electrical power | Electrical hardwire connection point | |
| *3* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 2.1.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Determine speed | Pitsword | |
| *1* | | Display pitsword output | Underwater log | |
| *2* | | Receive electrical power | Electrical hardwire connection point | |
| *3* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Alter existing course | Rudder | |
| *1* | | Control rudder movement locally | After steering gear | |
| *2* | | Control rudder movement remotely | Helm | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Uses same rudder hydraulic system |

**FR/DP Table**

**Index: 2.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Control rudder movement locally | After steering gear | |
| *1* | | Input desired rudder angle | Wheel | |
| *2* | | Display desired rudder angle | Indicator gage | |
| *3* | | Display actual rudder position | Rudder angle indicator | |
| *4* | | Produce desired rudder angle | Rudder hydraulic system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | x | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *4* | *1* | Calibration problem may cause actual not to be desired |

**FR/DP Table**

**Index: 2.2.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Produce desired rudder angle | Rudder hydraulic system | |
| *1* | | Hold hydraulic oil | Hydraulic oil sump | |
| *2* | | Supply / return hydraulic oil | Pumps | |
| *3* | | Start / stop hydraulic oil flow | Valves | |
| *4* | | Direct hydraulic oil flow | Solenoid valves | |
| *5* | | Transport hydraulic oil | Hydraulic oil piping | |
| *6* | | Determine hydraulic oil quantity | Gages measuring hydraulic oil level / Sight glasses | |
| *7* | | Determine hydraulic oil pressure | Pressure gages | |
| *8* | | Transfer control between local / remote stations | Transfer valve | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *8* | | Valve allows control from either after steering or helm |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* |
|---|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O | O |
| *FR.#.5* | O | X | X | O | X | O | O | O |
| *FR.#.6* | O | O | O | O | O | X | O | O |
| *FR.#.7* | O | O | O | O | O | O | X | O |
| *FR.#.8* | O | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 2.2.1.4.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / return hydraulic oil | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 2.2.1.4.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Direct hydraulic oil flow | Solenoid valves | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 2.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Control rudder movement remotely | Helm | |
| *1* | | Input desired rudder angle | Wheel | |
| *2* | | Display desired rudder angle | Indicator gage | |
| *3* | | Display actual rudder position | Rudder angle indicator | |
| *4* | | Produce desired rudder angle | Rudder hydraulic system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | x | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *4* | *1* | Calibration problem may cause actual not to be desired |

**FR/DP Table**

**Index: 2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Maneuver alongside pier | Bow thrusters / APU's | |
| *1* | | Ensure maneuverability to port / starboard | Pivotable (360 degrees) mount | |
| *2* | | Control thruster direction / thrust locally | Thruster local control station | |
| *3* | | Control thruster direction / thrust remotely | Thruster control station | |
| *4* | | Receive electrical power | Electrical connection point for hardwiring | |
| *5* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | O | X | X | O | O |
| *FR.#.4* | O | O | O | X | O |
| *FR.#.5* | O | O | O | X | X |

**FR/DP Table**

**Index: 2.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Control thruster direction / thrust locally | Thruster local control station | |
| *1* | | Input desired thruster direction and power | Local control handle | |
| *2* | | Display input combination | Indicator gage | |
| *3* | | Produce desired direction / thrust combination | Thruster control air system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | x | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Local control handle may not produce desired combination due to calibration problem. |

**FR/DP Table**

**Index: 2.3.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Produce desired direction / thrust combination | Thruster control air system | |
| *1* | | Increase air pressure to required pressure | Air compressor | |
| *2* | | Hold air at required pressure | Air flasks | |
| *3* | | Start /stop air flow | Valves | |
| *4* | | Transport air to flask / thruster control | Air piping | |
| *5* | | Determine air pressure | Pressure gages | |
| *6* | | Transfer control between local / remote stations | Transfer valve | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *6* | | Valve transfers control between local thruster control station and thruster control station |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O |
| *FR.#.3* | X | O | X | O | O | O |
| *FR.#.4* | X | O | X | X | O | O |
| *FR.#.5* | O | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Require pressure differential to cause air flow |
| *4* | *1* | Require pressure differential to cause air flow (transport) |
| *4* | *3* | Require pressure differential to cause air flow (transport) |

**FR/DP Table**

**Index: 2.3.2.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Increase air pressure to required pressure | Air compressor | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 2.3.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Control thruster direction / thrust remotely | Thruster control station | |
| *1* | | Input desired thruster direction and power | Control handle | |
| *2* | | Display input combination | Indicator gage | |
| *3* | | Produce desired direction / thrust combination | Thruster control air system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | x | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Control handle may not produce desired combination due to calibration problem |

**FR/DP Table**

**Index:**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | | | |
| *3* | | Neutralize enemy targets | Combat systems configuration | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| ***FR.#.1*** | X | O | O |
| ***FR.#.2*** | O | X | O |
| ***FR.#.3*** | O | O | X |

**FR/DP Table**

**Index: 3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Neutralize enemy targets | Combat systems configuration | |
| *1* | | Detect targets | Ship's sensors | |
| *2* | | Classify targets | Surveillance systems with identification protocols | |
| *3* | | Engage targets | Weapons systems | |
| *4* | | Operate as "node" sharing information within supersystem | Combat systems networking protocol (NTDS, JMCIS, etc.) | |
| *5* | | Provide target prosecution flexibility | Embarked helicopter | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *4* | | Navy Tactical Data System, Joint Management Combat Information System |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 |
|---|---|---|---|---|---|
| FR.#.1 | X | O | O | O | O |
| FR.#.2 | X | X | O | O | O |
| FR.#.3 | X | x | X | O | O |
| FR.#.4 | X | x | x | X | O |
| FR.#.5 | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| 2 | 1 | Target sensed before classified |
| 3 | 1 | Target sensed before engaged |
| 3 | 2 | Target sensed before engaged |
| 4 | 1 | Target sensed before information can be shared via network |
| 4 | 2 | Target sensed before information can be shared via network |
| 4 | 3 | Target sensed before information can be shared via network |

**FR/DP Table**

**Index: 3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Detect targets | Ship's sensors | |
| 1 | | Detect surface and shore based targets | Surface search radar (2D) | |
| 2 | | Detect subsurface targets | Sonar | |
| 3 | | Detect airborne targets | Air search radar (3D) | |
| 4 | | Detect electromagnetic (EM) emissions | Electronic countermeasures (ECM) surveillance antennas | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 |
|---|---|---|---|---|
| FR.#.1 | X | O | O | O |
| FR.#.2 | O | X | O | O |
| FR.#.3 | O | O | X | O |
| FR.#.4 | O | O | O | X |

**FR/DP Table**

**Index: 3.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Detect surface and shore based targets | Surface search radar (2D) | |
| *1* | | Switch between transmit / receive modes | Duplexer | |
| *2* | | Transmit / receive EM pulses | Antenna | |
| *3* | | Process EM data | Computer | |
| *4* | | Display contacts | Radar repeater screen | |
| *5* | | Receive electrical power | Electrical hardwire connection point | |
| *6* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | X | X | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O |
| *FR.#.4* | O | O | O | X | O | O |
| *FR.#.5* | O | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Duplexer must operate or antenna is only in one mode |

**FR/DP Table**

**Index: 3.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Detect subsurface targets | Sonar | |
| *1* | | Detect subsurface contacts without additionally compromising position | Passive sonar (towed array "tail") | |
| *2* | | Detect subsurface contacts with compromising position | Active sonar (sonar dome) | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Constructed of passive (listen only) hydrophones |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 3.1.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Detect subsurface contacts without additionally compromising position | Passive sonar (towed array "tail") | |
| *1* | | Filter / process (amplify) acoustic data | Computer | |
| *2* | | Display acoustic data | Passive sonar display screen | |
| *3* | | Store towed array | Reel | |
| *4* | | Deploy / retrieve towed array | Towed array hydraulic system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | x | X | O | O |
| ***FR.#.3*** | O | O | X | O |
| ***FR.#.4*** | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Data displayed in readable form only when processed |

**FR/DP Table**

**Index: 3.1.2.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Deploy / retrieve towed array | Towed array hydraulic system | |
| *1* | | Hold hydraulic oil | Hydraulic oil sump | |
| *2* | | Supply / return hydraulic oil flow | Pumps | |
| *3* | | Start / stop hydraulic oil flow | Valves | |
| *4* | | Direct hydraulic oil flow | Solenoid valves | |
| *5* | | Transport hydraulic oil to propeller / sump | Hydraulic oil piping | |
| *6* | | Determine hydraulic oil quantity | Gages measuring hydraulic oil level / Sight glasses | |
| *7* | | Determine hydraulic oil pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O |
| *FR.#.5* | O | X | X | O | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 3.1.2.1.4.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / return hydraulic oil flow | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 3.1.2.1.4.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Direct hydraulic oil flow | Solenoid valves | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 3.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Detect subsurface contacts with compromising position | Active sonar (sonar dome) | |
| *1* | | Process acoustic data | Computer | |
| *2* | | Transmit / receive sound pulses | Dual purpose hydrophones | |
| *3* | | Vary acoustic transmission range | Acoustic signal strength control | |
| *4* | | Display contacts | Active sonar display screen | |
| *5* | | Receive electrical power | Electrical hardwire connection point | |
| *6* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | X | X | O | O | O | O |
| *FR.#.3* | O | x | X | O | O | O |
| *FR.#.4* | O | O | O | X | O | O |
| *FR.#.5* | O | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Computer also controls time between transmissions to ensure receipt of return |

**FR/DP Table**

**Index: 3.1.2.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Transmit / receive sound pulses | Dual purpose hydrophones | |
| *1* | | Position hydrophones | Sonar dome | |
| *2* | | Protect hydrophones | Sonar dome window | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 3.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Detect airborne targets | Air search radar (3D) | |
| ***1*** | | Switch between transmit / receive modes | Duplexer | |
| ***2*** | | Transmit / receive EM pulses | Antenna | |
| ***3*** | | Process EM data | Computer | |
| ***4*** | | Display contacts | Radar repeater screen | |
| ***5*** | | Receive electrical power | Electrical hardwire connection point | |
| ***6*** | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | ***DP.#.1*** | ***DP.#.2*** | ***DP.#.3*** | ***DP.#.4*** | ***DP.#.5*** | ***DP.#.6*** |
|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O |
| ***FR.#.2*** | X | X | O | O | O | O |
| ***FR.#.3*** | O | O | X | O | O | O |
| ***FR.#.4*** | O | O | O | X | O | O |
| ***FR.#.5*** | O | O | O | O | X | O |
| ***FR.#.6*** | O | O | O | O | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| ***2*** | ***1*** | Duplexer must operate or antenna is only in one mode |

**FR/DP Table**

**Index: 3.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Detect electromagnetic (EM) emissions | Electronic countermeasures (ECM) surveillance antennas | |
| ***1*** | | Filter / process (amplify) EM data received | Computer | |
| ***2*** | | Display EM data | ECM display screen | |
| ***3*** | | Receive electrical power | Electrical hardwire connection point | |
| ***4*** | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 |
|---|---|---|---|---|
| FR.#.1 | X | O | O | O |
| FR.#.2 | O | X | O | O |
| FR.#.3 | O | O | X | O |
| FR.#.4 | O | O | X | X |

**FR/DP Table**

**Index: 3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Classify targets | Surveillance systems with identification protocols | |
| 1 | | Classify surface and airborne targets electronically | Identification friend / foe (IFF) system | |
| 2 | | Classify subsurface targets | Passive sonar signature identification protocol | |
| 3 | | Classify EM emissions | EM signature identification library | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 |
|---|---|---|---|
| FR.#.1 | X | O | O |
| FR.#.2 | O | X | O |
| FR.#.3 | O | O | X |

**FR/DP Table**

**Index: 3.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Classify surface and airborne targets electronically | Identification friend / foe (IFF) system | |
| 1 | | Receive IFF signal | IFF antenna | |
| 2 | | Interpret IFF signal | Computer with database | |
| 3 | | Display IFF signal data | IFF display screen | |
| 4 | | Receive electrical power | Electrical hardwire connection point | |
| 5 | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | O | X | O | O |
| ***FR.#.4*** | O | O | O | X | O |
| ***FR.#.5*** | O | O | O | X | X |

**FR/DP Table**

**Index: 3.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Classify subsurface targets | Passive sonar signature identification protocol | |
| ***1*** | | Receive sonar signature data | Transfer protocol | |
| ***2*** | | Interpret passive sonar signature | Computer with database | |
| ***3*** | | Display target data | Passive sonar display | |
| ***4*** | | Receive electrical power | Electrical hardwire connection point | |
| ***5*** | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | O | X | O | O |
| ***FR.#.4*** | O | O | O | X | O |
| ***FR.#.5*** | O | O | O | X | X |

**FR/DP Table**

**Index: 3.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Classify EM emissions | EM signature identification library | |
| *1* | | Receive EM emissions data | Transfer protocol | |
| *2* | | Interpret EM emissions comparing to stored library | Computer | |
| *3* | | Display classification data | ECM display screen | |
| *4* | | Receive electrical power | Electrical hardwire connection point | |
| *5* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | O | O | X | O | O |
| *FR.#.4* | O | O | O | X | O |
| *FR.#.5* | O | O | O | X | X |

**FR/DP Table**

**Index: 3.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Engage targets | Weapons systems | |
| *1* | | Engage long range surface / shore based targets | Surface to surface / land attack missile system (Tomahawk) | |
| *2* | | Engage short range surface / shore based targets | Naval gun | |
| *3* | | Engage subsurface targets | Torpedo and depth charge delivery system | |
| *4* | | Engage airborne targets | Surface to air missile system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | x | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | x | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Could also use surface to surface missile system to attack short range targets |
| *4* | *1* | Same method of storage (VLS cells) Same loading system (crane) |

**FR/DP Table**

**Index: 3.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Engage long range surface / shore based targets | Surface to surface / land attack missile system (Tomahawk) | |
| *1* | | Store missiles | Canisters (VLS cells) | |
| *2* | | Activate launching system | Targeting transfer protocol | |
| *3* | | Launch missiles | Missile launch switch | |
| *4* | | Guide missiles to target | Guidance system (integral to missile) | |
| *5* | | Track missile's trajectory | Missile system fire control radar | |
| *6* | | Allow simultaneous launches | Computer | |
| *7* | | Receive electrical power | Electrical hardwire connection point | |
| *8* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* |
|---|---|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O | O | O | O |
| ***FR.#.3*** | O | O | X | O | O | O | O | O |
| ***FR.#.4*** | O | O | O | X | O | O | O | O |
| ***FR.#.5*** | O | O | O | O | X | O | O | O |
| ***FR.#.6*** | O | X | X | O | X | X | O | O |
| ***FR.#.7*** | O | O | O | O | O | O | X | O |
| ***FR.#.8*** | O | O | O | O | O | O | X | X |

**FR/DP Table**

**Index: 3.3.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Store missiles | Canisters (VLS cells) | |
| *1* | | Load canisters | Crane | |
| *2* | | Contain toxic launching gases | Holding tank | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 3.3.1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Load canisters | Crane | |
| *1* | | Carry load's weight | Boom, wire, and hook | |
| *2* | | Maneuver in to required position | Crane hydraulic system | |
| *3* | | Receive electrical power | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | O | X | O | O |
| ***FR.#.3*** | O | O | X | O |
| ***FR.#.4*** | O | O | X | X |

**FR/DP Table**

**Index: 3.3.1.1.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Maneuver in to required position | Crane hydraulic system | |
| *1* | | Hold hydraulic oil | Hydraulic oil sump | |
| *2* | | Supply / return hydraulic oil flow | Pumps | |
| *3* | | Start / stop hydraulic oil flow | Valves | |
| *4* | | Direct hydraulic oil flow | Solenoid valves | |
| *5* | | Transport hydraulic oil to propeller / sump | Hydraulic oil piping | |
| *6* | | Determine hydraulic oil quantity | Gages measuring hydraulic oil level / Sight glasses | |
| *7* | | Determine hydraulic oil pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O | O | O |
| ***FR.#.3*** | O | X | X | O | O | O | O |
| ***FR.#.4*** | O | X | X | X | O | O | O |
| ***FR.#.5*** | O | X | X | O | X | O | O |
| ***FR.#.6*** | O | O | O | O | O | X | O |
| ***FR.#.7*** | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 3.3.1.1.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / return hydraulic oil flow | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 3.3.1.1.1.2.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Direct hydraulic oil flow | Solenoid valves | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | ***DP.#.1*** | ***DP.#.2*** |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 3.3.1.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Track missile's trajectory | Missile system fire control radar | |
| *1* | | Switch between transmit / receive modes | Duplexer | |
| *2* | | Transmit / receive EM pulses | Antenna | |
| *3* | | Process EM data | Computer | |
| *4* | | Display contacts | Radar repeater screen | |
| *5* | | Receive electrical power | Electrical hardwire connection point | |
| *6* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | X | X | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O |
| *FR.#.4* | O | O | O | X | O | O |
| *FR.#.5* | O | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Duplexer must operate or antenna is only in one mode |

**FR/DP Table**

**Index: 3.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Engage short range surface / shore based targets | Naval gun | |
| *1* | | Support gun operations | Gun support features | |
| *2* | | Activate firing system | Targeting transfer protocol | |
| *3* | | Maneuver gun in to firing position | Gun hydraulic system | |
| *4* | | Fire gun | Gun firing switch | |
| *5* | | Track projectile's trajectory | Gun fire control radar | |
| *6* | | Receive electrical power | Electrical hardwire connection point | |
| *7* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O |
| *FR.#.4* | O | O | O | X | O | O | O |
| *FR.#.5* | O | O | O | O | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | X | X |

**FR/DP Table**

**Index: 3.3.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Support gun operations | Gun support features | |
| *1* | | Store shells and gunpowder | Armory | |
| *2* | | Transport shells and gunpower to gun barrel | Elevator | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 3.3.2.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Transport shells and gunpower to gun barrel | Elevator | |
| *1* | | Move up / down | Elevator hydraulic system | |
| *2* | | Lock in position | Brake | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 3.3.2.1.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Move up / down | Elevator hydraulic system | |
| *1* | | Hold hydraulic oil | Hydraulic oil sump | |
| *2* | | Supply / return hydraulic oil flow | Pumps | |
| *3* | | Start / stop hydraulic oil flow | Valves | |
| *4* | | Direct hydraulic oil flow | Solenoid valves | |
| *5* | | Transport hydraulic oil to gun / sump | Hydraulic oil piping | |
| *6* | | Determine hydraulic oil quantity | Gages measuring hydraulic oil level / Sight glasses | |
| *7* | | Determine hydraulic oil pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O |
| *FR.#.5* | O | X | X | O | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 3.3.2.1.2.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / return hydraulic oil flow | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 3.3.2.1.2.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Direct hydraulic oil flow | Solenoid valves | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 3.3.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Maneuver gun in to firing position | Gun hydraulic system | |
| *1* | | Hold hydraulic oil | Hydraulic oil sump | |
| *2* | | Supply / return hydraulic oil flow | Pumps | |
| *3* | | Start / stop hydraulic oil flow | Valves | |
| *4* | | Direct hydraulic oil flow | Solenoid valves | |
| *5* | | Transport hydraulic oil to propeller / sump | Hydraulic oil piping | |
| *6* | | Determine hydraulic oil quantity | Gages measuring hydraulic oil level / Sight glasses | |
| *7* | | Determine hydraulic oil pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O |
| *FR.#.5* | O | X | X | O | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 3.3.2.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / return hydraulic oil flow | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 3.3.2.3.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Direct hydraulic oil flow | Solenoid valves | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 3.3.2.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Track projectile's trajectory | Gun fire control radar | |
| *1* | | Switch between transmit / receive modes | Duplexer | |
| *2* | | Transmit / receive EM pulses | Antenna | |
| *3* | | Process EM data | Computer | |
| *4* | | Display contacts | Radar repeater screen | |
| *5* | | Receive electrical power | Electrical hardwire connection point | |
| *6* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | X | X | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O |
| *FR.#.4* | O | O | O | X | O | O |
| *FR.#.5* | O | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Duplexer must operate or antenna is only in one mode |

**FR/DP Table**

**Index: 3.3.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Engage subsurface targets | Torpedo and depth charge delivery system | |
| *1* | | Support torpedo operations | Torpedo support features | |
| *2* | | Charge torpedo for launch | Breach | |
| *3* | | Launch torpedos | Torpedo launch switch | |
| *4* | | Guide torpedo to target | Guidance system integral to torpedo | |
| *5* | | Track torpedo's trajectory | Passive sonar | |
| *6* | | Receive electrical power | Electrical hardwire connection point | |
| *7* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O | O |
| *FR.#.4* | O | O | O | X | O | O | O |
| *FR.#.5* | O | O | O | O | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | X | X |

**FR/DP Table**

**Index: 3.3.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Support torpedo operations | Torpedo support features | |
| *1* | | Store torpedos | Torpedo room racks | |
| *2* | | Hold torpedos for launch | Torpedo tubes | |
| *3* | | Transport torpedos to torpedo tubes | Rollers and rigging gear | |
| *4* | | Secure torpedo in tube | Torpedo tube door | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | O | X |

**FR/DP Table**

**Index: 3.3.3.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Secure torpedo in tube | Torpedo tube door | |
| *1* | | Ensure air/watertightness | Seal | |
| *2* | | Secure opening | "Dogging" devices | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Seal ensures complete securing of opening |

**FR/DP Table**

**Index: 3.3.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Charge torpedo for launch | Breach | |
| *1* | | Connect to torpedo tube | Zirc fitting | |
| *2* | | Pressurize with air | High pressure air system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 3.3.3.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Pressurize with air | High pressure air system | |
| *1* | | Increase air pressure to required pressure | Air compressor | |
| *2* | | Hold air at required pressure | Air flasks | |
| *3* | | Start /stop air flow | Valves | |
| *4* | | Transport air to flask / breach | Air piping | |
| *5* | | Determine air pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | X | O | X | O | O |
| *FR.#.4* | X | O | X | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Require pressure differential to cause air flow |
| *4* | *1* | Require pressure differential to cause air flow (transport) |
| *4* | *3* | Require pressure differential to cause air flow (transport) |

**FR/DP Table**

**Index: 3.3.3.2.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Increase air pressure to required pressure | Air compressor | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 |
|---|---|---|
| FR.#.1 | X | O |
| FR.#.2 | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| 2 | 1 | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 3.3.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Engage airborne targets | Surface to air missile system | |
| 1 | | Store missiles | Canisters (VLS cells) | |
| 2 | | Activate launching system | Targeting transfer protocol | |
| 3 | | Launch missiles | Missile launch switch | |
| 4 | | Track missile's flight path | Missile fire control radar | |
| 5 | | Guide missile to target | Illuminators | |
| 6 | | Allow simultaneous launches | Computer | |
| 7 | | Receive electrical power | Electrical hardwire connection point | |
| 8 | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 | DP.#.6 | DP.#.7 | DP.#.8 |
|---|---|---|---|---|---|---|---|---|
| FR.#.1 | X | O | O | O | O | O | O | O |
| FR.#.2 | O | X | O | O | O | O | O | O |
| FR.#.3 | O | O | X | O | O | O | O | O |
| FR.#.4 | O | O | O | X | O | O | O | O |
| FR.#.5 | O | O | O | X | X | O | O | O |
| FR.#.6 | O | X | X | X | X | X | O | O |
| FR.#.7 | O | O | O | O | O | O | X | O |
| FR.#.8 | O | O | O | O | O | O | X | X |

**FR/DP Table**

**Index: 3.3.4.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Store missiles | Canisters (VLS cells) | |
| *1* | | Load canisters | Crane | |
| *2* | | Contain toxic launching gases | Holding tank | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Same crane used for FR3.3.1, therfore not decomposed |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 3.3.4.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Guide missile to target | Illuminators | |
| *1* | | "Paint" target with narrow concentrated EM radiation beam | Emmitter antenna | |
| *2* | | Track target | Missile fire control radar | |
| *3* | | Receive electrical power | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Control panel | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | | Same radar used to satisly FR3.3.4.4, therefore not decomposed |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 3.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Operate as "node" sharing information within supersystem | Combat systems networking protocol (NTDS, JMCIS, etc.) | |
| *1* | | Transmit target information | Transmit protocol | |
| *2* | | Receive target information | Receive protocol | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index:**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | | | |
| *4* | | Protect from enemy attack | Countermeasures methods | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | O | X |

**FR/DP Table**

**Index: 4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Protect from enemy attack | Countermeasures methods | |
| *1* | | Neutralize enemy weapon's effect by "hard kill" | Self defense weapons | |
| *2* | | Neutralize enemy weapon's effect by "soft kill" | Self defense decoys | |
| *3* | | Reduce liklihood of enemy detection | Signatures reduction | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Employing the layered self defense philosophy for airborne threats |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | x | X | O |
| *FR.#.3* | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| 2 | 1 | Weapon could actually acquire and destroy self defense weapon vs ship |
| 2 | 3 | Weapon could actually acquire and destroy self defense weapon vs ship |

**FR/DP Table**

**Index: 4.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Neutralize enemy weapon's effect by "hard kill" | Self defense weapons | |
| *1* | | Neutralize long range airborne weapon (missile) | Long range surface to air missile system (Nato Sea Sparrow) | |
| *2* | | Neutralize medium range airborne weapon (missile) | Medium range surface to air missile system (RAM) | |
| *3* | | Neutralize short range airborne weapon (missile) | Close in weapons system (CIWS) | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | | RAM = rolling airframe missile system |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | x | X | O |
| *FR.#.3* | O | x | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| 2 | 1 | Some overlap in coverage of long and medium range systems |

**FR/DP Table**

**Index: 4.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Neutralize long range airborne weapon (missile) | Long range surface to air missile system (Nato Sea Sparrow) | |
| *1* | | Store missiles | Canisters (VLS cells) | |
| *2* | | Activate launching system | Targeting transfer protocol | |
| *3* | | Launch missiles | Missile launch switch | |
| *4* | | Track missile's flight path | Missile fire control radar | |
| *5* | | Guide missile to target | Illuminators | |
| *6* | | Allow simultaneous launches | Computer | |
| *7* | | Receive electrical power | Electrical hardwire connection point | |
| *8* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* |
|---|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O | O | O |
| *FR.#.4* | O | O | O | X | O | O | O | O |
| *FR.#.5* | O | O | O | X | X | O | O | O |
| *FR.#.6* | O | X | X | X | X | X | O | O |
| *FR.#.7* | O | O | O | O | O | O | X | O |
| *FR.#.8* | O | O | O | O | O | O | X | X |

**FR/DP Table**

**Index: 4.1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Store missiles | Canisters (VLS cells) | |
| *1* | | Load canisters | Crane | |
| *2* | | Contain toxic launching gases | Holding tank | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Same crane used for FR3.3.1, therfore not decomposed |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 4.1.1.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Guide missile to target | Illuminators | |
| *1* | | "Paint" target with narrow concentrated EM radiation beam | Emmitter antenna | |
| *2* | | Track target | Missile fire control radar | |
| *3* | | Receive electrical power | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Control panel | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | | Same radar used to satisly FR3.3.4.4, therefore not decomposed |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 4.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Neutralize medium range airborne weapon (missile) | Medium range surface to air missile system (RAM) | |
| *1* | | Store missiles | Canisters (RAM cells) | |
| *2* | | Activate launching system | Targeting transfer protocol | |
| *3* | | Launch missiles | Missile launch switch | |
| *4* | | Guide missiles to target | Infrared guidance system integral to missile | |
| *5* | | Track missile's flight trajectory | Missile fire control radar | |
| *6* | | Allow simultaneous launches | Computer | |
| *7* | | Receive electrical power | Electrical hardwire connection point | |
| *8* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* |
|---|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O | O | O |
| *FR.#.4* | O | O | O | X | O | O | O | O |
| *FR.#.5* | O | O | O | O | X | O | O | O |
| *FR.#.6* | O | X | X | O | X | X | O | O |
| *FR.#.7* | O | O | O | O | O | O | X | O |
| *FR.#.8* | O | O | O | O | O | O | X | X |

**FR/DP Table**

**Index: 4.1.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Store missiles | Canisters (RAM cells) | |
| *1* | | Load canisters | Crane | |
| *2* | | Contain toxic launching gases | Holding tank | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 4.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Neutralize short range airborne weapon (missile) | Close in weapons system (CIWS) | |
| *1* | | Store projectiles | Integral storage bin | |
| *2* | | Activate firing system | Automatic arming switch | |
| *3* | | Track target and projectiles trajectory | Integral fire control radar | |
| *4* | | Guide projectiles to target | Projectile-target position matching protocol | |
| *5* | | Fire projectiles until target destroyed | Computer | |
| *6* | | Receive electrical power | Electrical hardwire connection point | |
| *7* | | Energize / de-energize | Control panel | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *5* | | Receives signal from radar detecting low flying fast moving target within specified range |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O | O |
| *FR.#.4* | O | O | X | X | O | O | O |
| *FR.#.5* | O | O | X | X | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | X | X |

**FR/DP Table**

**Index: 4.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Neutralize enemy weapon's effect by "soft kill" | Self defense decoys | |
| *1* | | Neutralize acoustic targeted weapons | Deployable noisemakers (Nixie) | |
| *2* | | Neutralize home on EM weapons | Electronic countercountermeasures (ECCM) | |
| *3* | | Neutralize home on IR weapons | Deployable IR decoys (Torch) | |
| *4* | | Neutralize home on object weapons | Deployable false targets (Chaf) | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | | Jamming |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | O | X |

**FR/DP Table**

**Index: 4.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Neutralize acoustic targeted weapons | Deployable noisemakers (Nixie) | |
| *1* | | Hold noisemaker | Canister | |
| *2* | | Charge noisemaker for launch | Breach | |
| *3* | | Launch noisemaker | Noisemaker launch switch | |
| *4* | | Track noisemaker's trajectory | Passive sonar | |
| *5* | | Receive electrical power | Electrical hardwire connection point | |
| *6* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O |
| *FR.#.4* | O | O | O | X | O | O |
| *FR.#.5* | O | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | X | X |

**FR/DP Table**

**Index: 4.2.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Charge noisemaker for launch | Breach | |
| *1* | | Connect to canister | Zirc fitting | |
| *2* | | Pressurize with air | High pressure air system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 4.2.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Pressurize with air | High pressure air system | |
| *1* | | Increase air pressure to required pressure | Air compressor | |
| *2* | | Hold air at required pressure | Air flasks | |
| *3* | | Start /stop air flow | Valves | |
| *4* | | Transport air to flask / breach | Air piping | |
| *5* | | Determine air pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | X | O | X | O | O |
| *FR.#.4* | X | O | X | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Require pressure differential to cause air flow |
| *4* | *1* | Require pressure differential to cause air flow (transport) |
| *4* | *3* | Require pressure differential to cause air flow (transport) |

**FR/DP Table**

**Index: 4.2.1.2.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Increase air pressure to required pressure | Air compressor | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 4.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Neutralize home on EM weapons | Electronic countercountermeasures (ECCM) | |
| *1* | | Determine EM frequency being targeted | Computer | |
| *2* | | Select respective EM frequency to be jammed | Frequency selection protocol | |
| *3* | | Jam respective EM spectrum range | Antenna emitting high intensity EM pulse | |
| *4* | | Receive electrical power | Electrical hardwire connection point | |
| *5* | | Energize / de-energize | Control panel | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *3* | | Constant EM emission |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | O | X | O | O |
| ***FR.#.4*** | O | O | O | X | O |
| ***FR.#.5*** | O | O | O | X | X |

**FR/DP Table**

**Index: 4.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Neutralize home on IR weapons | Deployable IR decoys (Torch) | |
| *1* | | Hold decoy | Canister | |
| *2* | | Launch decoy | IR decoy launch switch | |
| *3* | | Receive electrical power | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 |
|---|---|---|---|---|
| FR.#.1 | X | O | O | O |
| FR.#.2 | O | X | O | O |
| FR.#.3 | O | O | X | O |
| FR.#.4 | O | O | X | X |

**FR/DP Table**

**Index: 4.2.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Neutralize home on object weapons | Deployable false targets (Chaf) | |
| 1 | | Hold false target | Canister | |
| 2 | | Launch false target | Chaf launch switch | |
| 3 | | Receive electrical power | Electrical hardwire connection point | |
| 4 | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 |
|---|---|---|---|---|
| FR.#.1 | X | O | O | O |
| FR.#.2 | O | X | O | O |
| FR.#.3 | O | O | X | O |
| FR.#.4 | O | O | X | X |

**FR/DP Table**

**Index: 4.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Reduce liklihood of enemy detection | Signatures reduction | |
| 1 | | Reduce detection by acoustic sensing means | Acoustic masking and vibration damping | |
| 2 | | Reduce detection by electromagnetic (EM) sensing means | Exploitation of radar EM pulse characteristics | |
| 3 | | Reduce detection by infrared (IR) sensing means | Dissipation of heat sources | |
| 4 | | Reduce detection by EM surveillance means | EM radiation control (EMCON conditions) | |
| 5 | | Reduce detection by magnetic field actuated ordnance | Degaussing system | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *4* | | Operational consideration noted |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | O | X | O | O |
| ***FR.#.4*** | O | O | O | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**FR/DP Table**

**Index: 4.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Reduce detection by acoustic sensing means | Acoustic masking and vibration damping | |
| *1* | | Mask propeller noise | Prarie system | |
| *2* | | Mask hull noise | Masker system | |
| *3* | | Absorb vibrations | Vibration absorbant decks (rubber matting) | |
| *4* | | Absorb engine vibrations (specifically) | Vibration absorbant mounts | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | X | X | O | O |
| ***FR.#.3*** | O | O | X | O |
| ***FR.#.4*** | O | O | x | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Share common air source |

**FR/DP Table**

**Index: 4.3.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Mask propeller noise | Prarie system | |
| *1* | | Increase air pressure to required pressure | Air compressor | |
| *2* | | Hold air at required pressure | Air flasks | |
| *3* | | Start /stop air flow | Valves | |
| *4* | | Transport air to flask / hub nozzles | Air piping | |
| *5* | | Discharge air | Hub nozzles | |
| *6* | | Determine air pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O | O |
| ***FR.#.3*** | X | O | X | O | O | O |
| ***FR.#.4*** | X | O | X | X | O | O |
| ***FR.#.5*** | O | O | O | O | X | O |
| ***FR.#.6*** | O | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Require pressure differential to cause air flow |
| *4* | *1* | Require pressure differential to cause air flow (transport) |
| *4* | *3* | Require pressure differential to cause air flow (transport) |

**FR/DP Table**

**Index: 4.3.1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Increase air pressure to required pressure | Air compressor | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 4.3.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Mask hull noise | Masker system | |
| *1* | | Increase air pressure to required pressure | Air compressor | |
| *2* | | Hold air at required pressure | Air flasks | |
| *3* | | Start /stop air flow | Valves | |
| *4* | | Transport air to flask / masker nozzles | Air piping | |
| *5* | | Discharge air | Masker nozzles | |
| *6* | | Determine air pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O | O |
| ***FR.#.3*** | X | O | X | O | O | O |
| ***FR.#.4*** | X | O | X | X | O | O |
| ***FR.#.5*** | O | O | O | O | X | O |
| ***FR.#.6*** | O | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Require pressure differential to cause air flow |
| *4* | *1* | Require pressure differential to cause air flow (transport) |
| *4* | *3* | Require pressure differential to cause air flow (transport) |

**FR/DP Table**

**Index: 4.3.1.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Increase air pressure to required pressure | Air compressor | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 4.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Reduce detection by electromagnetic (EM) sensing means | Exploitation of radar EM pulse characteristics | |
| *1* | | Minimize radar cross section (RCS) | Superstructure construction | |
| *2* | | Cause radar EM pulse to not return to source | Radar absorbant material (RAM) applied to superstructure | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Hull characteristics not included because of decision made to produce highest level decoupled design equations |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 4.3.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Minimize radar cross section (RCS) | Superstructure construction | |
| ***1*** | | Redirect radar EM pulse | Sloped superstructure sides | |
| ***2*** | | Reduce ship's frontal / side areas | Superstructure arrangements/layout | |
| ***3*** | | Reduce structure that increases radar EM pulse reflective strength | Di/trihedral elimination | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| ***FR.#.1*** | X | O | O |
| ***FR.#.2*** | O | X | O |
| ***FR.#.3*** | O | O | X |

**FR/DP Table**

**Index: 4.3.2.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Reduce ship's frontal / side areas | Superstructure arrangements/layout | |
| ***1*** | | Enclose helicopter | Aircraft hanger | |
| ***2*** | | Enclose personnel and equipment | Deckhouse | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | x | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Hanger must also enclose personnel and equipment - main size concern is helo |

**Related Constraints**

| *No.* | *Parent* | *Keyword* | *Description* | *Comment* | *1* | *2* | *Verification* |
|---|---|---|---|---|---|---|---|
| *1* | | | Available deckhouse volume > Required deckhouse volume | | | * | |
| *2* | | | Available deckhouse area > Required deckhouse area | | | * | |
| *3* | | | Available hanger volume > Required hanger volume | | * | | |
| *4* | | | Available hanger area > Required hanger area | | * | | |

**FR/DP Table**

**Index: 4.3.2.1.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Enclose helicopter | Aircraft hanger | |
| *1* | | Ensure watertight integrity | Structure | |
| *2* | | Allow verticle clearance for helicopter | Hanger deck height | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 4.3.2.1.2.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Ensure watertight integrity | Structure | |
| *1* | | Provide external topside access without compromising watertight integrity | Watertight closable openings | |
| *2* | | Prevent water from entering through skin of ship | Exterior bulkhead construction | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | | Although extensive detail (therefore decomposition) is required to define structure construction adequately, decomposition stops - Limitation noted |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | If watertight openings don't work, water will enter |

**FR/DP Table**

**Index: 4.3.2.1.2.1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Provide external topside access without compromising watertight integrity | Watertight closable openings | |
| ***1*** | | Ensure watertightness | Seals | |
| ***2*** | | Secure opening | "Dogging" devices | |
| ***3*** | | Allow vertical access to space | Hatches | |
| ***4*** | | Allow horizontal access to space | Doors | |
| ***5*** | | Allow visual access to space | Portholes | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | X | X | O | O | O |
| ***FR.#.3*** | O | X | X | O | O |
| ***FR.#.4*** | O | X | O | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Seal ensures complete sealing of opening |

**FR/DP Table**

**Index: 4.3.2.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Enclose personnel and equipment | Deckhouse | |
| *1* | | Ensure watertight integrity | Structure | |
| *2* | | Allow verticle clearance for personnel and equipment | Number of decks and average height | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 4.3.2.1.2.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Ensure watertight integrity | Structure | |
| *1* | | Provide external topside access without compromising watertight integrity | Watertight closable openings | |
| *2* | | Prevent water from entering through skin of ship | Exterior bulkhead construction | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | | Although extensive detail (therefore decomposition) is required to define structure construction adequately, decomposition stops - Limitation noted |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | If watertight openings don't work, water will enter |

**FR/DP Table**

**Index: 4.3.2.1.2.2.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Provide external topside access without compromising watertight integrity | Watertight closable openings | |
| *1* | | Ensure watertightness | Seals | |
| *2* | | Secure opening | "Dogging" devices | |
| *3* | | Allow vertical access to space | Hatches | |
| *4* | | Allow horizontal access to space | Doors | |
| *5* | | Allow visual access to space | Portholes | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | X | X | O | O | O |
| ***FR.#.3*** | O | X | X | O | O |
| ***FR.#.4*** | O | X | O | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Seal ensures complete sealing of opening |

**FR/DP Table**

**Index: 4.3.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Reduce detection by infrared (IR) sensing means | Dissipation of heat sources | |
| *1* | | Dissipate engine exhaust heat | Stack boundary layer infrared supression system (BLISS) | |
| *2* | | Dissipate general space heat | Ventilation insulation | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 4.3.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Dissipate engine exhaust heat | Stack boundary layer infrared supression system (BLISS) | |
| *1* | | Allow ambient air to enter stack | Openings in stack side | |
| *2* | | Mix hot stack gases with ambient air | Venturi effect created by escaping exhaust gases | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Openings must be unobstructed for mixing to happen |

**FR/DP Table**

**Index: 4.3.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Reduce detection by magnetic field actuated ordnance | Degaussing system | |
| *1* | | Input magnetic signature adjustments | Degaussing control station | |
| *2* | | Adjust transverse magnetic signature | M-Coil | |
| *3* | | Adjust longitudinal magnetic signature | L-Coil | |
| *4* | | Adjust vertical magnetic signature | P-Coil | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | | MUST CHECK NAMES OF ALL COILS |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | O | X | O | O |
| ***FR.#.3*** | O | O | X | O |
| ***FR.#.4*** | O | O | O | X |

**FR/DP Table**

**Index: 4.3.5.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Input magnetic signature adjustments | Degaussing control station | |
| *1* | | Determine respective magnetic field strength | Indicator gages | |
| *2* | | Increase / decrease magnetic field strength | Control knob | |
| *3* | | Receive electrical power | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Energize / de-energize | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | X | X | O | O |
| ***FR.#.3*** | O | O | X | O |
| ***FR.#.4*** | O | O | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Shows amount of adjustment |

**FR/DP Table**

**Index:**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | | | |
| ***5*** | | Conduct sustained underway operations | Support / Auxiliary systems and features | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| ***5*** | This FR also includes the functions that allow a ship to operate in port, and then transition from an in port configuration to an underway configuration | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | O | X | O | O |
| ***FR.#.4*** | O | O | O | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**FR/DP Table**

**Index: 5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Conduct sustained underway operations | Support / Auxiliary systems and features | |
| ***1*** | | Ensure habitable conditions | Crew support / habitability features | |
| ***2*** | | Maintain equipment in operating condition | Maintenance philosophy | |
| ***3*** | | Communicate information | Communications equipment | |
| ***4*** | | Combat damage | Damage control (DC) systems and equipment | |
| ***5*** | | Secure position while underway | Anchoring system | |
| ***6*** | | Secure position while in port | Mooring system | |
| ***7*** | | Provide electrical power | Electrical system | |
| ***8*** | | Provide fuel source | Fuel system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* |
|---|---|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O | O | O | O |
| ***FR.#.3*** | O | O | X | O | O | O | O | O |
| ***FR.#.4*** | X | O | O | X | O | O | O | O |
| ***FR.#.5*** | O | O | O | O | X | O | O | O |
| ***FR.#.6*** | O | O | O | O | O | X | O | O |
| ***FR.#.7*** | O | O | O | O | O | O | X | O |
| ***FR.#.8*** | O | O | O | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *4* | *1* | Installed ventilation system used for desmoking |

**FR/DP Table**

**Index: 5.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Ensure habitable conditions | Crew support / habitability features | |
| *1* | | Supply stores (food) sufficient to feed the crew for stores period (XX days) | Provisions loadout | |
| *2* | | Supply fresh water | Potable water system | |
| *3* | | Control climate for crew comfort and machinery performance | Climate control system | |
| *4* | | Provide for crew hygiene | Plumbing system | |
| *5* | | Support feeding of crew | Food service equipment | |
| *6* | | Illuminate spaces | Lighting system | |
| *7* | | Allow crew escape when necessary | Life boats | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 | DP.#.6 | DP.#.7 |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O |
| *FR.#.5* | X | X | X | X | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *5* | *1* | Provisions loadout are components comprising meals |
| *5* | *2* | Provisions loadout are components comprising meals |
| *5* | *3* | Provisions loadout are components comprising meals |
| *5* | *4* | Provisions loadout are components comprising meals |

**FR/DP Table**

**Index: 5.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply stores (food) sufficient to feed the crew for stores period (XX days) | Provisions loadout | |
| *1* | | Store provisions not requiring temperature control | Dry goods storage spaces | |
| *2* | | Store provisions requiring temperature control | Refrigerator and freezer spaces | |
| *3* | | Onload provisions | Replenishment at sea (RAS) system | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | | Decomposition to include machinery required, but not accomplished - Noted |
| *3* | | Requires further decomposition, but not accomplished - Limitation noted |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | O | X |

**FR/DP Table**

**Index: 5.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply fresh water | Potable water system | |
| *1* | | Provide salt water for desalination | Sea water system | |
| *2* | | Remove salt from water | Evaporator | |
| *3* | | Hold potable water | Potable water tanks | |
| *4* | | Supply potable water to tank / designated systems | Potable water pumps | |
| *5* | | Start / stop potable water flow | Valves | |
| *6* | | Transport potable water | Potable water piping | |
| *7* | | Determine potable water quantity | Gages reading potable water tank level | |
| *8* | | Determine potable water pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* |
|---|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O | O | O |
| *FR.#.4* | O | O | O | X | O | O | O | O |
| *FR.#.5* | O | O | O | X | X | O | O | O |
| *FR.#.6* | O | O | O | X | X | X | O | O |
| *FR.#.7* | O | O | O | O | O | O | X | O |
| *FR.#.8* | O | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.1.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide salt water for desalination | Sea water system | |
| *1* | | Supply / remove sea water | Sea water pumps | |
| *2* | | Start / stop sea water flow | Valves | |
| *3* | | Transport sea water | Sea water piping | |
| *4* | | Determine sea water pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | X | X | O | O |
| ***FR.#.3*** | X | X | X | O |
| ***FR.#.4*** | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Sea water must be supplied to start flow |
| *3* | *1* | Sea water must be supplied for transport |
| *3* | *2* | Sea water must be supplied for transport |

**FR/DP Table**

**Index: 5.1.2.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove sea water | Sea water pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Electrical power must be received to energize |

**FR/DP Table**

**Index: 5.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Remove salt from water | Evaporator | |
| *1* | | Evaporate sea water (Flash to steam) | Electric heat source (resistor) | |
| *2* | | Collect condensate | Condensate reservior | |
| *3* | | Collect and discharge salt | Salt water reservoir and piping | |
| *4* | | Determine salt level in condensate | Salinity cells | |
| *5* | | Discharge water not having acceptable salt content | Dump valve | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Standard practice also uses steam as heat source. But to keep design decoupled can't use (to make steam, already use potable water system). |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | O | X | O | O |
| ***FR.#.4*** | O | O | O | X | O |
| ***FR.#.5*** | O | O | X | O | X |

**FR/DP Table**

**Index: 5.1.2.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Evaporate sea water (Flash to steam) | Electric heat source (resistor) | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Electrical power must be received to energize |

**FR/DP Table**

**Index: 5.1.2.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Supply potable water to tank / designated systems | Potable water pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Control climate for crew comfort and machinery performance | Climate control system | |
| *1* | | Recirculate/replenish air within space | Ventilation system | |
| *2* | | Heat ship spaces | Steam system | |
| *3* | | Cool ship spaces | Chill water system | |
| *4* | | Maintain humidity level | Dehumidifier | |
| *5* | | Determine space temperature | Thermometer | |
| *6* | | Set desired space temperature | Thermostat | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O |
| *FR.#.4* | O | O | O | X | O | O |
| *FR.#.5* | O | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.1.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Recirculate/replenish air within space | Ventilation system | |
| *1* | | Supply air to / remove air from space | Fans | |
| *2* | | Start / stop air flow into space | Vents | |
| *3* | | Transport air to space | Ducting | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | X | X | O |
| *FR.#.3* | X | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Fresh air must be supplied to start flow |
| *3* | *1* | Fresh air must be supplied for transport |
| *3* | *2* | Fresh air must be supplied for transport |

**FR/DP Table**

**Index: 5.1.3.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply air to / remove air from space | Fans | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.1.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Heat ship spaces | Steam system | |
| *1* | | Produce steam | Auxiliary boiler | |
| *2* | | Supply steam | Pressure differential | |
| *3* | | Start / stop steam flow | Valves | |
| *4* | | Transport steam to desired location | Steam piping | |
| *5* | | Ensure steam pressure does not exceed specified pressure | Boiler safety valve | |
| *6* | | Determine sream pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O |
| *FR.#.4* | O | X | X | X | O | O |
| *FR.#.5* | O | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.1.3.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Produce steam | Auxiliary boiler | |
| *1* | | Produce heat source | Boiler flame | |
| *2* | | Provide water with proper chemistry | Boiler water / Feed water (BW/FW) system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 5.1.3.2.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Produce heat source | Boiler flame | |
| *1* | | Ignite flame | Ignitor | |
| *2* | | Ensure continuously burning flame | Boiler fuel system | |
| *3* | | Contain flame | Refractory | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | O | X |

**FR/DP Table**

**Index: 5.1.3.2.1.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Ensure continuously burning flame | Boiler fuel system | |
| *1* | | Receive fuel from fuel transfer system | Piping connection | |
| *2* | | Supply fuel | Boiler fuel pump | |
| *3* | | Start / stop fuel flow | Valves | |
| *4* | | Transport fuel to engine | Boiler fuel piping | |
| *5* | | Determine fuel pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | O | X | X | O | O |
| *FR.#.4* | O | X | X | X | O |
| *FR.#.5* | O | O | O | O | X |

**FR/DP Table**

**Index: 5.1.3.2.1.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply fuel | Boiler fuel pump | |
| *1* | | Activate / de-activate pump | Engine rotation | |
| *2* | | Control fuel output | Engine rotation speed | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Speed is characteristic of rotation |

**FR/DP Table**

**Index: 5.1.3.2.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide water with proper chemistry | Boiler water / Feed water (BW/FW) system | |
| *1* | | Receive water from potable water system | Piping connection | |
| *2* | | Hold feed water | Feed water tanks | |
| *3* | | Supply feed water / Remove boiler water | Feed pumps | |
| *4* | | Start / stop boiler water / feed water flow | Valves | |
| *5* | | Transport feed water to boiler / Return boiler water to feed tank | Boiler water / Feed water piping | |
| *6* | | Determine feed water quantity | Gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O |
| *FR.#.4* | O | O | X | X | O | O |
| *FR.#.5* | O | O | X | X | X | O |
| *FR.#.6* | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.1.3.2.1.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply feed water / Remove boiler water | Feed pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.1.3.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Cool ship spaces | Chill water system | |
| *1* | | Receive ambient temperature water | Sea water suction piping | |
| *2* | | Produce chill water | Air conditioning units | |
| *3* | | Supply / remove chill water | Chill water pumps | |
| *4* | | Start / stop chill water flow | Valves | |
| *5* | | Transport chill water | Chill water piping | |
| *6* | | Determine chill water temperature | Temperature gages | |
| *7* | | Determine chill water pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O | O |
| *FR.#.4* | O | O | X | X | O | O | O |
| *FR.#.5* | O | O | X | X | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.1.3.3.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove chill water | Chill water pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide for crew hygiene | Plumbing system | |
| *1* | | Provide means for washing | Sinks and showers | |
| *2* | | Eliminate waste products | Sewage system | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Associated drainage piping eliminates waste water |

**FR/DP Table**

**Index: 5.1.4.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide means for washing | Sinks and showers | |
| *1* | | Supply fresh washing water | Potable water system | |
| *2* | | Heat washing water | Steam system | |
| *3* | | Remove waste water | Drainage piping | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | O | X |

**FR/DP Table**

**Index: 5.1.4.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Eliminate waste products | Sewage system | |
| *1* | | Remove waste products | Flushing water (sea water) system | |
| *2* | | Start / stop waste products flow | Valves | |
| *3* | | Transport human waste products | Sewage piping | |
| *4* | | Hold and treat waste products | CHT tanks | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Standard practice is to use firemain. But to eliminate coupling, exclusive system used. |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | X | X | X | O |
| *FR.#.4* | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Flushing water system must be activated to initiate transport |
| *3* | *2* | Flushing water system must be activated to initiate transport |

**FR/DP Table**

**Index: 5.1.4.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Remove waste products | Flushing water (sea water) system | |
| *1* | | Deposit human waste for removal | Toilets and urinals | |
| *2* | | Supply flushing water | Sea water pumps | |
| *3* | | Start / stop flushing water flow | Valves | |
| *4* | | Transport flushing water | Sea water piping | |
| *5* | | Determine flushing water pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | X | X | O | O |
| ***FR.#.4*** | O | X | X | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**FR/DP Table**

**Index: 5.1.4.2.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply flushing water | Sea water pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.1.4.2.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Hold and treat waste products | CHT tanks | |
| *1* | | Determine CHT level | Gages reading tank level | |
| *2* | | Discharge treated waste products | CHT pumps | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 5.1.4.2.4.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Discharge treated waste products | CHT pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.1.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Support feeding of crew | Food service equipment | |
| *1* | | Cook food | Galley equipment | |
| *2* | | Clean cooking equipment | Scullery, dishwashers | |
| *3* | | Provide drinking water | Skuttlebutts (Drinking fountains) | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | O | X |

**FR/DP Table**

**Index: 5.1.5.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Cook food | Galley equipment | |
| *1* | | Bake food | Ovens | |
| *2* | | Fry food | Stove ranges and deep fat fryers | |
| *3* | | Boil food | Steam kettles | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | O | X |

**FR/DP Table**

**Index: 5.1.5.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Bake food | Ovens | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must provide electrical power to energize |

**FR/DP Table**

**Index: 5.1.5.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Fry food | Stove ranges and deep fat fryers | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | ***DP.#.1*** | ***DP.#.2*** |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must provide electrical power to energize |

**FR/DP Table**

**Index: 5.1.5.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Boil food | Steam kettles | |
| *1* | | Provide steam | Steam system | |
| *2* | | Determine steam pressure | Pressure gages | |

**Total Design Matrix Information**

| | ***DP.#.1*** | ***DP.#.2*** |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 5.1.5.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Clean cooking equipment | Scullery, dishwashers | |
| *1* | | Supply fresh water | Potable water system | |
| *2* | | Heat cleaning water | Steam system | |
| *3* | | Remove waste water | Drainage piping | |
| *4* | | Receive electrical power | Electrical hardwire connection point | |
| *5* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | O | X | O | O |
| ***FR.#.4*** | O | O | O | X | O |
| ***FR.#.5*** | O | O | O | X | X |

**FR/DP Table**

**Index: 5.1.5.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide drinking water | Skuttlebutts (Drinking fountains) | |
| *1* | | Provide potable water | Potable water system | |
| *2* | | Cool water | Self contained refrigeration unit | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 5.1.6**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Illuminate spaces | Lighting system | |
| *1* | | Provide light source | Light bulbs | |
| *2* | | Hold / secure light sources | Sockets | |
| *3* | | Receive electrical power | Electrical hardwire connection points | |
| *4* | | Energize / de-energize | Switches | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 5.1.7**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Allow crew escape when necessary | Life boats | |
| *1* | | Store life boats | Capsules | |
| *2* | | Launch life boats | Davits | |
| *3* | | Inflate life boats | Hydrostatic pressure activated switches | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | O | X |

**FR/DP Table**

**Index: 5.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Maintain equipment in operating condition | Maintenance philosophy | |
| *1* | | Monitor equipment operation | Watchstanders / Automated machines / Combination | |
| *2* | | Repair euipment when necessary | Trained technicians (ship's crew / shore based) | |
| *3* | | Provide required repair parts | Supply repair parts inventory | |
| *4* | | Ensure non-interupted operation during repairs | Machinery redundancy | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *4* | | In parallel configuration |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | x | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | X | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Watchstanders monitoring equipment could also conduct repairs |
| *4* | *1* | Must switch to operating unit |

**FR/DP Table**

**Index: 5.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide required repair parts | Supply repair parts inventory | |
| *1* | | Store inventory on board | Supply storerooms | |
| *2* | | Replace used items / Provide items not held | Shore based supply system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 5.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Communicate information | Communications equipment | |
| ***1*** | | Communicate with external units | Transmit and receive antennas | |
| ***2*** | | Communicate internally | Internal communications (IC) equipment | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 5.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Communicate with external units | Transmit and receive antennas | |
| ***1*** | | Communicate with other ships, commercial or navy (voice) | Bridge to bridge radio | |
| ***2*** | | Communicate with other navy units, ships or shorebased | Radio room equipment | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 5.3.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Communicate with other ships, commercial or navy (voice) | Bridge to bridge radio | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.3.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Communicate with other navy units, ships or shorebased | Radio room equipment | |
| *1* | | Communicate in text format | Teletype machines | |
| *2* | | Communicate in voice or data format | Radio circuits (UHF, VHF, SATCOM) | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 5.3.1.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Communicate in text format | Teletype machines | |
| *1* | | Communicate without secure transfer | Non-secure radio circuit | |
| *2* | | Communicate with secure transfer | Encrypted radio circuit | |
| *3* | | Receive electrical power | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 5.3.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Communicate in voice or data format | Radio circuits (UHF, VHF, SATCOM) | |
| *1* | | Communicate without secure transfer | Non-secure radio circuit | |
| *2* | | Communicate with secure transfer | Encrypted radio circuit | |
| *3* | | Receive electrical power | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 5.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Communicate internally | Internal communications (IC) equipment | |
| *1* | | Communicate voice one-way | General announcing system (1-MC) | |
| *2* | | Communicate two-way voice without requiring electrical power | Sound powered phone system | |
| *3* | | Communicate voice two-way dialog | Telephone network | |
| *4* | | Communicate data two-way | Computer network | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | x | X | O |
| *FR.#.4* | O | O | O | X |

**FR/DP Table**

**Index: 5.3.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Communicate voice one-way | General announcing system (1-MC) | |
| *1* | | Amplify voice | Amplifier | |
| *2* | | Transmit sound | Speakers | |
| *3* | | Receive electrical power | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | X | X |

**FR/DP Table**

**Index: 5.3.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Communicate two-way voice without requiring electrical power | Sound powered phone system | |
| *1* | | Provide connection point to network | Sound powered telephone jacks | |
| *2* | | Connect sound powered phones | Sound powered telephone cabling | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Jacks are end of connection |

**FR/DP Table**

**Index: 5.3.2.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Communicate voice two-way dialog | Telephone network | |
| *1* | | Provide connection point to network | Telephone jacks | |
| *2* | | Connect telephones | Telephone cabling | |
| *3* | | Receive electrical power for entire network | Electrical hardwire connection point | |
| *4* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | X | X | O | O |
| ***FR.#.3*** | O | O | X | O |
| ***FR.#.4*** | O | O | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Jacks are connection end point |

**FR/DP Table**

**Index: 5.3.2.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Communicate data two-way | Computer network | |
| *1* | | Control data flow between computers | Network server | |
| *2* | | Provide connection point to network | Computer jacks | |
| *3* | | Connect computers | Fiber optic computer cabling | |
| *4* | | Receive electrical power for each computer and network server | Electrical hardwire connection point | |
| *5* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | O | O | O | X | O |
| *FR.#.5* | O | O | O | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Server makes electronic connection |
| *3* | *2* | Server makes electronic connection |

**FR/DP Table**

**Index: 5.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Combat damage | Damage control (DC) systems and equipment | |
| *1* | | Fight fires | Fire fighting systems | |
| *2* | | Control flooding | Dewatering systems | |
| *3* | | Repair hull damage | Hull repair resources | |
| *4* | | Display DC situation | Damage Control Central situation display | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | O | X | O | O |
| ***FR.#.3*** | O | O | X | O |
| ***FR.#.4*** | O | O | O | X |

**FR/DP Table**

**Index: 5.4.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Fight fires | Fire fighting systems | |
| *1* | | Fight Class A fire | Ship's Firemain | |
| *2* | | Fight class B fire | Aqueous film forming foam (AFFF) system | |
| *3* | | Fight Class C fire | Fixed carbon dioxide (CO2) system | |
| *4* | | Desmoke space | Installed ventilation system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | X | X | O | O |
| ***FR.#.3*** | O | O | X | O |
| ***FR.#.4*** | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Firemain supplies water to AFFF system |

**FR/DP Table**

**Index: 5.4.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Fight Class A fire | Ship's Firemain | |
| *1* | | Access firemain at designated locations | Fire stations | |
| *2* | | Supply fire fighting water | Fire pumps | |
| *3* | | Start / stop fire fighting water flow | Valves | |
| *4* | | Transport fire fighting water throughout ship | Firemain piping | |
| *5* | | Determine firemain pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | O | X | X | O | O |
| *FR.#.4* | O | X | X | X | O |
| *FR.#.5* | O | O | O | O | X |

**FR/DP Table**

**Index: 5.4.1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Access firemain at designated locations | Fire stations | |
| *1* | | Manually direct flow | Fire hose | |
| *2* | | Deliver fire fighting water in necessary pattern and velocity | Nozzle | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 5.4.1.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply fire fighting water | Fire pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.4.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Fight class B fire | Aqueous film forming foam (AFFF) system | |
| *1* | | Access AFFF at designated locations | AFFF stations | |
| *2* | | Supply AFFF | AFFF pumps | |
| *3* | | Start / stop AFFF flow | Valves | |
| *4* | | Transport AFFF to station | AFFF piping | |
| *5* | | Determine AFFF pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | O | X | X | O | O |
| *FR.#.4* | O | X | X | X | O |
| *FR.#.5* | O | O | O | O | X |

**FR/DP Table**

**Index: 5.4.1.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Access AFFF at designated locations | AFFF stations | |
| *1* | | Dilute AFFF and pressurize system | Firemain water | |
| *2* | | Ensure proper AFFF / firemain water mixture | Proportioner | |
| *3* | | Manually direct flow | Hose | |
| *4* | | Deliver AFFF mixture in necessary pattern and velocity | Nozzle | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | O | X |

**FR/DP Table**

**Index: 5.4.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply AFFF | AFFF pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.4.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Fight Class C fire | Fixed carbon dioxide ($CO_2$) system | |
| *1* | | Hold pressurized $CO_2$ | Cylinders | |
| *2* | | Activate $CO_2$ | Lever / trigger | |
| *3* | | Transport $CO_2$ from cylinder to hose | $CO_2$ piping | |
| *4* | | Determine $CO_2$ pressure | Pressure gages | |
| *5* | | Manually direct flow | Hose | |
| *6* | | Deliver $CO_2$ in focused stream | Horn | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O | O |
| ***FR.#.3*** | O | O | X | O | O | O |
| ***FR.#.4*** | O | O | O | X | O | O |
| ***FR.#.5*** | O | O | O | O | X | O |
| ***FR.#.6*** | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.4.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Control flooding | Dewatering systems | |
| *1* | | Remove water from engine rooms and selected spaces (normal conditions) | Bilge suction system | |
| *2* | | Remove water from engine rooms and selected spaces (emergengy conditions) | Eductor system | |
| *3* | | Remove water from any space | P-250 pumps and portable hoses | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | Selected spaces are bounded by bilge | |
| *2* | Selected spaces are bounded by bilge | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | X | X | O |
| *FR.#.3* | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Systems use common piping |

**FR/DP Table**

**Index: 5.4.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Remove water from engine rooms and selected spaces (normal conditions) | Bilge suction system | |
| *1* | | Produce system suction | Bilge suction pumps | |
| *2* | | Start / stop "dirty" bilge water flow | Valves | |
| *3* | | Transport "dirty" bilge water | Bilge suction piping | |
| *4* | | Determine suction pressure | Pressure gages | |
| *5* | | Ensure waste oil does not discharge | Oil / water separator | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | X | X | X | O | O |
| *FR.#.4* | O | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | To start flow, need suction |
| *3* | *1* | Suction must be provided to transport |
| *3* | *2* | Suction must be provided to transport |

**FR/DP Table**

**Index: 5.4.2.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Produce system suction | Bilge suction pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Require electrical power to energize |

**FR/DP Table**

**Index: 5.4.2.1.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Ensure waste oil does not discharge | Oil / water separator | |
| *1* | | Start / stop waste oil flow | Valves (waste oil) | |
| *2* | | Transport waste oil | Waste oil piping | |
| *3* | | Hold waste oil | Waste oil tank | |
| *4* | | Determine oil content in bilge water discharge | Sensor | |
| *5* | | Display oil content in bilge water discharge | Indicator gage | |
| *6* | | Start / stop "clean" bilge water flow | Valves (bilge water) | |
| *7* | | Discharge "clean" bilge water | "Clean" bilge water discharge piping | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O | O |
| ***FR.#.2*** | X | X | O | O | O | O | O |
| ***FR.#.3*** | O | O | X | O | O | O | O |
| ***FR.#.4*** | O | O | O | X | O | O | O |
| ***FR.#.5*** | O | O | O | O | X | O | O |
| ***FR.#.6*** | O | O | O | O | O | X | O |
| ***FR.#.7*** | O | O | O | O | O | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Require proper valve alignment for transport |

**FR/DP Table**

**Index: 5.4.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Remove water from engine rooms and selected spaces (emergengy conditions) | Eductor system | |
| *1* | | Produce emergency system suction | Eductors | |
| *2* | | Start / stop "dirty" bilge water flow | Valves | |
| *3* | | Transport "dirty" bilge water | Bilge suction piping | |
| *4* | | Determine suction pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O |
| ***FR.#.2*** | X | X | O | O |
| ***FR.#.3*** | X | X | X | O |
| ***FR.#.4*** | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Require suction to start flow |
| *3* | *1* | Need suction for transportation |
| *3* | *2* | Need suction for transportation |

**FR/DP Table**

**Index: 5.4.2.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Produce emergency system suction | Eductors | |
| *1* | | Create suction force | Venturi effect caused by firemain flow | |
| *2* | | Start / stop "dirty" bilge water discharge | Eductor valves | |
| *3* | | Discharge "dirty" bilge water | Eductor piping | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| ***FR.#.1*** | X | O | O |
| ***FR.#.2*** | O | X | O |
| ***FR.#.3*** | O | X | X |

**FR/DP Table**

**Index: 5.4.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Repair hull damage | Hull repair resources | |
| *1* | | Accomplish temporary repairs | Shoring | |
| *2* | | Accomplish semi-permanant repairs | Welding equipment | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 5.5**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Secure position while underway | Anchoring system | |
| *1* | | Connect to sea floor | Anchor | |
| *2* | | Hold ship's position | Anchor chain | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | x | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Anchor determines start of anchor chain, therefore fixes position |

**FR/DP Table**

**Index: 5.5.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Hold ship's position | Anchor chain | |
| *1* | | Direct anchor chain trajectory off ship | Hawspipe | |
| *2* | | Heave in / Pay out anchor chain | Anchor windlass | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 5.5.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Heave in / Pay out anchor chain | Anchor windlass | |
| *1* | | Rotate windlass | Windlass hydraulic system | |
| *2* | | Stop rotation and secure windlass | Windlass brake | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 |
|---|---|---|
| FR.#.1 | X | O |
| FR.#.2 | O | X |

**FR/DP Table**

**Index: 5.5.2.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Rotate windlass | Windlass hydraulic system | |
| 1 | | Hold hydraulic oil | Hydraulic oil sump | |
| 2 | | Supply / return hydraulic oil flow | Pumps | |
| 3 | | Start / stop hydraulic oil flow | Valves | |
| 4 | | Direct hydraulic oil flow | Solenoid valves | |
| 5 | | Transport hydraulic oil to windlass / sump | Hydraulic oil piping | |
| 6 | | Determine hydraulic oil quantity | Gages measuring hydraulic oil level / Sight glasses | |
| 7 | | Determine hydraulic oil pressure | Pressure gages | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 | DP.#.6 | DP.#.7 |
|---|---|---|---|---|---|---|---|
| FR.#.1 | X | O | O | O | O | O | O |
| FR.#.2 | O | X | O | O | O | O | O |
| FR.#.3 | O | X | X | O | O | O | O |
| FR.#.4 | O | X | X | X | O | O | O |
| FR.#.5 | O | X | X | O | X | O | O |
| FR.#.6 | O | O | O | O | O | X | O |
| FR.#.7 | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.5.2.2.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Supply / return hydraulic oil flow | Pumps | |
| 1 | | Receive electrical power | Electrical hardwire connection point | |
| 2 | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.5.2.2.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Direct hydraulic oil flow | Solenoid valves | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.6**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Secure position while in port | Mooring system | |
| *1* | | Connect to pier | Mooring lines | |
| *2* | | Provide securing point on ship | Bitts and chocks | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 5.6.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Connect to pier | Mooring lines | |
| *1* | | Tighten / slacken mooring lines | Capstans | |
| *2* | | Control position / distance from pier | Mooring line tension | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Tension increased/decreased by capstans |

**FR/DP Table**

**Index: 5.6.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Tighten / slacken mooring lines | Capstans | |
| *1* | | Rotate capstan | Capstan hydraulic system | |
| *2* | | Stop rotation and secure capstan | Capstan brake | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 5.6.1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Rotate capstan | Capstan hydraulic system | |
| *1* | | Hold hydraulic oil | Hydraulic oil sump | |
| *2* | | Supply / return hydraulic oil flow | Pumps | |
| *3* | | Start / stop hydraulic oil flow | Valves | |
| *4* | | Direct hydraulic oil flow | Solenoid valves | |
| *5* | | Transport hydraulic oil to capstan / sump | Hydraulic oil piping | |
| *6* | | Determine hydraulic oil quantity | Gages measuring hydraulic oil level / Sight glasses | |
| *7* | | Determine hydraulic oil pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* |
|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O |
| *FR.#.5* | O | X | X | O | X | O | O |
| *FR.#.6* | O | O | O | O | O | X | O |
| *FR.#.7* | O | O | O | O | O | O | X |

**Index: 5.6.1.1.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / return hydraulic oil flow | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.6.1.1.1.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Direct hydraulic oil flow | Solenoid valves | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.7**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Provide electrical power | Electrical system | |
| *1* | | Generate electrical power | Ship's service generators | |
| *2* | | Generate electrical power in emergency situation | Emergency diesel generator | |
| *3* | | Distribute electrical power | Electrical switchboards | |
| *4* | | Transport electrical power to equipment | Cabling | |
| *5* | | Isolate equipment locally | Circuit breakers | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | O | O | X | O | O |
| *FR.#.4* | O | O | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**FR/DP Table**

**Index: 5.7.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Generate electrical power | Ship's service generators | |
| *1* | | Provide prime mover to turn rotor | Generator engine | |
| *2* | | Create electric field | Relative motion between rotor and stator | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Engine turns rotor |

**FR/DP Table**

**Index: 5.7.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide prime mover to turn rotor | Generator engine | |
| *1* | | Provide inertia to start engine | Starting air system | |
| *2* | | Provide fuel for continuous engine operation | GE fuel system | |
| *3* | | Cool engine | GE lube oil system | |
| *4* | | Provide air to support engine combustion | Engine inlet ducting | |
| *5* | | Remove combustion products | Engine exhaust ducting | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 |
|---|---|---|---|---|---|
| **FR.#.1** | X | O | O | O | O |
| **FR.#.2** | O | X | O | O | O |
| **FR.#.3** | O | O | X | O | O |
| **FR.#.4** | O | O | O | X | O |
| **FR.#.5** | O | O | O | O | X |

**Related Constraints**

| No. | Parent | Keyword | Description | Comment | 1 | 2 | 3 | 4 | 5 | Verification |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | Fuel supply rate must support combined engine specific fuel comsumption (sfc) | Constraint vs FR added because engines already set at higher level. Selected engines have associated sfc which does not change. | | * | | | | |

**FR/DP Table**

**Index: 5.7.1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Provide inertia to start engine | Starting air system | |
| 1 | | Increase air pressure to required pressure | Air compressor | |
| 2 | | Hold air at required pressure | Air flasks | |
| 3 | | Start /stop air flow | Valves | |
| 4 | | Transport air to flask / engine | Air piping | |
| 5 | | Determine air pressure | Pressure gages | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 | DP.#.5 |
|---|---|---|---|---|---|
| **FR.#.1** | X | O | O | O | O |
| **FR.#.2** | O | X | O | O | O |
| **FR.#.3** | X | O | X | O | O |
| **FR.#.4** | X | O | X | X | O |
| **FR.#.5** | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Require pressure differential to cause air flow |
| *4* | *1* | Require pressure differential to cause air flow (transport) |
| *4* | *3* | Require pressure differential to cause air flow (transport) |

**FR/DP Table**

**Index: 5.7.1.1.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Increase air pressure to required pressure | Air compressor | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Need electricity (via hardwire connection point) to energize / de-energize |

**FR/DP Table**

**Index: 5.7.1.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide fuel for continuous engine operation | GE fuel system | |
| *1* | | Receive fuel from fuel transfer system | Piping connection | |
| *2* | | Supply fuel | Engine fuel pump | |
| *3* | | Start / stop fuel flow | Valves | |
| *4* | | Transport fuel to engine | Engine fuel piping | |
| *5* | | Determine fuel pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | O | X | O | O | O |
| *FR.#.3* | O | X | X | O | O |
| *FR.#.4* | O | X | X | X | O |
| *FR.#.5* | O | O | O | O | X |

**FR/DP Table**

**Index: 5.7.1.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply fuel | Engine fuel pump | |
| *1* | | Activate / de-activate pump | Engine rotation | |
| *2* | | Control fuel output | Engine rotation speed | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Speed is characteristic of rotation |

**FR/DP Table**

**Index: 5.7.1.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Cool engine | GE lube oil system | |
| *1* | | Hold lube oil | GE lube oil sumps | |
| *2* | | Supply / remove lube oil | Pumps | |
| *3* | | Start / stop lube oil flow | Valves | |
| *4* | | Transport lube oil | GE lube oil piping | |
| *5* | | Determine lube oil quantity | Gages measuring sump level / Sight glasses | |
| *6* | | Determine lube oil pressure | Pressure gages | |
| *7* | | Determine lube oil temperature | Temperature gages | |
| *8* | | Cool lube oil | Sea water system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* |
|---|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O | O | O |
| *FR.#.4* | O | X | X | X | O | O | O | O |
| *FR.#.5* | O | O | O | O | X | O | O | O |
| *FR.#.6* | O | O | O | O | O | X | O | O |
| *FR.#.7* | O | O | O | O | O | O | X | O |
| *FR.#.8* | O | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.7.1.1.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove lube oil | Pumps | |
| *1* | | Activate / de-activate pumps | Engine rotation | |
| *2* | | Control lube oil output | Engine rotation speed | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Speed is characteristic of rotation |

**FR/DP Table**

**Index: 5.7.1.1.3.8**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Cool lube oil | Sea water system | |
| *1* | | Receive / discharge cooling water from / to sea | Hull openings | |
| *2* | | Supply / remove sea water | Pumps | |
| *3* | | Start / stop sea water flow | Valves | |
| *4* | | Transport sea water | Sea water piping | |
| *5* | | Determine sea water pressure | Pressure gages | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O |
| ***FR.#.3*** | O | X | X | O | O |
| ***FR.#.4*** | O | X | X | X | O |
| ***FR.#.5*** | O | O | O | O | X |

**FR/DP Table**

**Index: 5.7.1.1.3.8.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Supply / remove sea water | Pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 5.7.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Generate electrical power in emergency situation | Emergency diesel generator | |
| *1* | | Provide prime mover to generate electric field | Small deiesel engine | |
| *2* | | Transport electrical power to vital equipment | Emergency cabling | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | Vital equipment includes navigation lights and communications radio | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 5.7.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Distribute electrical power | Electrical switchboards | |
| *1* | | Connect switchboards | Main bus breaker | |
| *2* | | Connect to generators | 3-phase electrical cables | |
| *3* | | Determine electrical output | Indicator gages | |
| *4* | | Supply / remove equipment electrical power remotely | Bus ties (ABTs, MBTs) | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* |
|---|---|---|---|---|
| *FR.#.1* | X | O | O | O |
| *FR.#.2* | O | X | O | O |
| *FR.#.3* | O | O | X | O |
| *FR.#.4* | O | O | O | X |

**FR/DP Table**

**Index: 5.8**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide fuel source | Fuel system | |
| *1* | | Onload fuel | Fuel onload system / Fueling at sea (FAS) system | |
| *2* | | Store fuel in sufficient quantity | Fuel storage system | |
| *3* | | Provide fuel for machinery operation | Fuel service system | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *2* | Endurance range based on engine sfc when steaming at endurance speed<br>Electrical fuel requirement based on 24 hr average electrical load | |
| *3* | Machinery includes main propulsion engines, electrical generation engines, and auxilary boilers | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | X | X |

**FR/DP Table**

**Index: 5.8.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Onload fuel | Fuel onload system / Fueling at sea (FAS) system | |
| *1* | | Connect fuel hose | Fuel riser | |
| *2* | | Hold fuel hose securely | Coupling | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 5.8.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Store fuel in sufficient quantity | Fuel storage system | |
| *1* | | Hold fuel | Fuel storage tanks | |
| *2* | | Supply / remove fuel | Fuel pumps | |
| *3* | | Start / stop fuel flow | Valves | |
| *4* | | Transport fuel to selected location | Fuel piping | |
| *5* | | Determine fuel quantity | Gages measuring fuel tank level | |
| *6* | | Determine fuel pressure | Pressure gages | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *6* | Pressure only required when fuel being supplied to system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O |
| *FR.#.3* | O | X | X | O | O | O |
| *FR.#.4* | O | X | X | X | O | O |
| *FR.#.5* | O | O | O | O | X | O |
| *FR.#.6* | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.8.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove fuel | Fuel pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must provide electrical power to energize |

**FR/DP Table**

**Index: 5.8.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide fuel for machinery operation | Fuel service system | |
| *1* | | Receive fuel from fuel storage system | Piping connection | |
| *2* | | Hold fuel | Fuel service tanks | |
| *3* | | Supply / remove fuel | Fuel pumps | |
| *4* | | Start / stop fuel flow | Valves | |
| *5* | | Transport fuel to selected location | Fuel piping | |
| *6* | | Determine fuel quantity | Gages measuring fuel tank level | |
| *7* | | Determine fuel pressure | Pressure gages | |
| *8* | | Remove any existing sediment from fuel | Fuel purifier | |
| *9* | | Remove any existing water from fuel | Coalescer | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *7* | Done only when fuel bing supplied to system | |
| *8* | Done only when fuel being introduced to system | |
| *9* | Done only when fuel being introduced to system | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* | *DP.#.7* | *DP.#.8* | *DP.#.9* |
|---|---|---|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O | O | O | O |
| *FR.#.4* | O | O | X | X | O | O | O | O | O |
| *FR.#.5* | O | O | X | X | X | O | O | O | O |
| *FR.#.6* | O | O | O | O | O | X | O | O | O |
| *FR.#.7* | O | O | O | O | O | O | X | O | O |
| *FR.#.8* | O | O | O | O | O | O | O | X | O |
| *FR.#.9* | O | O | O | O | O | O | O | O | X |

**FR/DP Table**

**Index: 5.8.3.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove fuel | Fuel pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must provide electrical power to energize |

**FR/DP Table**

**Index:**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | | | |
| *6* | | Operate on surface of water | Hull form | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O |
| ***FR.#.2*** | O | X | O | O | O | O |
| ***FR.#.3*** | O | O | X | O | O | O |
| ***FR.#.4*** | O | O | O | X | O | O |
| ***FR.#.5*** | O | O | O | O | X | O |
| ***FR.#.6*** | O | O | O | O | O | X |

**FR/DP Table**

**Index: 6**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Operate on surface of water | Hull form | |
| *1* | | Enclose personnel and equipment | Hull | |
| *2* | | Support total ship weight | Displaced hull form volume | |
| *3* | | Minimize total resistance | Hull form characteristics (coefficients of form) | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| ***FR.#.1*** | X | O | O |
| ***FR.#.2*** | O | X | O |
| ***FR.#.3*** | X | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | LWL and B affect resistance |
| *3* | *2* | LWL and B affect resistance |

**FR/DP Table**

**Index: 6.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Enclose personnel and equipment | Hull | |
| *1* | | Allow linear placement of equipment | Hull extents | |
| *2* | | Allow verticle clearance for personnel and equipment | Number of decks and average deck height | |
| *3* | | Ensure watertight integrity | Hull structure | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | x | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *3* | *1* | Hull structural height must ensure longitudinal strength determined by LWL |

**FR/DP Table**

**Index: 6.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Allow linear placement of equipment | Hull extents | |
| *1* | | Facilitate longitudinal placement | Length on design waterline (LWL) | |
| *2* | | Facilitate transverse placement | Beam | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**Related Constraints**

| No. | Parent | Keyword | Description | Comment | 1 | 2 | Verification |
|---|---|---|---|---|---|---|---|
| 1 | | | Must contain machinery box beam | | | * | |

**FR/DP Table**

**Index: 6.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| P. | | Ensure watertight integrity | Hull structure | |
| 1 | | Provide access to all spaces without compromising watertight integrity | Watertight closable openings | |
| 2 | | Prevent water from entering over the sides | Depth at Station 10 (D10) | |
| 3 | | Prevent water from entering through skin of ship | Exterior hull construction | |
| 4 | | Prevent progressive flooding | Internal hull partitioning | |

**Total Design Matrix Information**

| | DP.#.1 | DP.#.2 | DP.#.3 | DP.#.4 |
|---|---|---|---|---|
| FR.#.1 | X | O | O | O |
| FR.#.2 | O | X | O | O |
| FR.#.3 | X | O | X | O |
| FR.#.4 | X | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| 3 | 1 | Watertight closable openings must secure to ensure complete watertightness |
| 4 | 1 | Watertight closable openings secure watertightness of interior bulkheads |

**Related Constraints**

| No. | Parent | Keyword | Description | Comment | 1 | 2 | 3 | 4 | Verification |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | | Must contain machinery box height | | | * | | | |
| 2 | | | D10 >= Ndecks x Hdk | | | * | | | |
| 3 | | | Must satisfy longitudinal strength criteria (D10 >= LWL/15) | | | * | | | |
| 4 | | | Keep deck edge above water at 25 deg heel | | | * | | | |

**FR/DP Table**

**Index: 6.1.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Provide access to all spaces without compromising watertight integrity | Watertight closable openings | |
| *1* | | Ensure watertightness | Seals | |
| *2* | | Secure opening | "Dogging" devices | |
| *3* | | Allow vertical access to space | Hatches | |
| *4* | | Allow horizontal access to space | Doors | |
| *5* | | Allow visual access to space | Portholes | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* |
|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O |
| *FR.#.2* | X | X | O | O | O |
| *FR.#.3* | O | X | X | O | O |
| *FR.#.4* | O | X | O | X | O |
| *FR.#.5* | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Seal ensures complete sealing of opening |

**FR/DP Table**

**Index: 6.1.3.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Prevent progressive flooding | Internal hull partitioning | |
| *1* | | Prevent longitudinal progressive flooding | Longitudinal watertight bulkheads | |
| *2* | | Prevent transverse progressive flooding | Transverse watertight bulkheads | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

**FR/DP Table**

**Index: 6.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Support total ship weight | Displaced hull form volume | |
| *1* | | Maintain constant displacement | Consistent loading philosophy | |
| *2* | | Maintain even transverse orientation (0 degree list) | Centerline and symmetric (port/stbd) liquid tanks | |
| *3* | | Maintain even longitudinal orientation (0 trim) | Longitudinal evenly spaced liquid tanks | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| ***FR.#.1*** | X | O | O |
| ***FR.#.2*** | X | X | O |
| ***FR.#.3*** | X | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Transverse placement must be considered in philosophy |
| *3* | *1* | Longitudinal placement must be considered in placement |

**FR/DP Table**

**Index: 6.2.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Maintain constant displacement | Consistent loading philosophy | |
| *1* | | Allow for weight additions and removals (other than burning fuel) | Ballast system | |
| *2* | | Allow for weight removal caused by fuel burning | Compensated fuel system | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | The ship must operate with a designated liquid load such that tanks are neither full, nor empty to always operate at the DWL. This allows for the removal and addition of weight. If weight is removed, additional ballast water is added keeping the total ship weight constant. Conversely, if weight is added, ballast water is removed. |
| *2* | | Required to maintain decoupled design. As fuel is burned, it is automatically replaced with salt water. |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | O | X |

**FR/DP Table**

**Index: 6.2.1.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Allow for weight additions and removals (other than burning fuel) | Ballast system | |
| *1* | | Hold ballast water | Ballast tanks | |
| *2* | | Negate free surface effect (FSE) | Baffels | |
| *3* | | Supply / remove ballast water | Pumps and eductors | |
| *4* | | Start / stop ballast water flow | Valves | |
| *5* | | Transport ballast water to selected location | Ballast water piping | |
| *6* | | Determine ballast water quantity | Gages indicating ballast tank levels | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| ***FR.#.1*** | X | O | O | O | O | O |
| ***FR.#.2*** | x | X | O | O | O | O |
| ***FR.#.3*** | O | O | X | O | O | O |
| ***FR.#.4*** | O | O | X | X | O | O |
| ***FR.#.5*** | O | O | X | X | X | O |
| ***FR.#.6*** | O | O | O | O | O | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Baffels must be designed to fit in tanks |

**FR/DP Table**

**Index: 6.2.1.1.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Supply / remove ballast water | Pumps and eductors | |
| ***1*** | | Receive electrical power | Electrical hardwire connection point | |
| ***2*** | | Energize / de-energize pump | Control panel | |

**Total Design Matrix Information**

| | ***DP.#.1*** | ***DP.#.2*** |
|---|---|---|
| ***FR.#.1*** | X | O |
| ***FR.#.2*** | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 6.2.1.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| ***P.*** | | Allow for weight removal caused by fuel burning | Compensated fuel system | |
| ***1*** | | Separate salt water from fuel | "False" deck in fuel transfer tanks | |
| ***2*** | | Supply / remove salt water | Salt water pumps | |
| ***3*** | | Start / stop salt water flow in appropriate direction | One way check valves | |
| ***4*** | | Direct salt water flow direction | Solenoid valves | |
| ***5*** | | Transport salt water to / from tank | Compensated fuel system piping | |
| ***6*** | | Determine salt water quantity | Gage indicating salt water level | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | As fuel is burned, deck rises up allowing salt water to fill empty space Upon resupplying fuel to tank, floor lowers forcing water out |
| *2* | | Operation must be coordinated with fuel burning and fuel transferring |
| *3* | Appropriate direction coresponds to onload or offload of water | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* | *DP.#.4* | *DP.#.5* | *DP.#.6* |
|---|---|---|---|---|---|---|
| *FR.#.1* | X | O | O | O | O | O |
| *FR.#.2* | O | X | O | O | O | O |
| *FR.#.3* | O | O | X | O | O | O |
| *FR.#.4* | O | X | O | X | O | O |
| *FR.#.5* | O | X | X | O | X | O |
| *FR.#.6* | O | O | O | O | O | X |

**FR/DP Table**

**Index: 6.2.1.2.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Supply / remove salt water | Salt water pumps | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize pump | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 6.2.1.2.4**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Direct salt water flow direction | Solenoid valves | |
| *1* | | Receive electrical power | Electrical hardwire connection point | |
| *2* | | Energize / de-energize pump | Control panel | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Must receive electrical power to energize |

**FR/DP Table**

**Index: 6.3**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Minimize total resistance | Hull form characteristics (coefficients of form) | |
| *1* | | Minimize residuary resistance | Hull form factors | |
| *2* | | Minimize friction resistance | Submerged hull / water interaction | |
| *3* | | Minimize air resistance | Frontal area | |

**FR/DP Comment**

| No. | Functional Requirements (FRs) | Design Parameters (DPs) |
|---|---|---|
| *1* | | Speed also affects resistance - resistance is directly porportional to velocity |
| *2* | | Speed also affects resistance - resistance is directly proportional to velocity |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* | *DP.#.3* |
|---|---|---|---|
| *FR.#.1* | X | O | O |
| *FR.#.2* | O | X | O |
| *FR.#.3* | O | O | X |

**FR/DP Table**

**Index: 6.3.1**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Minimize residuary resistance | Hull form factors | |
| *1* | | Minimize resistance caused by hull "fullness" | Maximum section coefficient (Cx) | |
| *2* | | Minimize resistance caused by underwater hull volume | Volumetric coefficient (Cv) | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | X | X |

**Comment for the Element of Design Matrix**

| i | j | Remarks |
|---|---|---|
| *2* | *1* | Cx affects underwater hull volume |

**FR/DP Table**

**Index: 6.3.2**

| No. | Name | Functional Requirements (FRs) | Design Parameters (DPs) | Verification |
|---|---|---|---|---|
| *P.* | | Minimize friction resistance | Submerged hull / water interaction | |
| *1* | | Produce viscous resistance forces (drag) | Relative motion between submerged hull and water | |
| *2* | | Produce contact between hull and water | Wetted surface area | |

**Total Design Matrix Information**

| | *DP.#.1* | *DP.#.2* |
|---|---|---|
| *FR.#.1* | X | O |
| *FR.#.2* | O | X |

# Appendix C

# MIT XIII-A Functional Ship Synthesis Model (DD13A Modelled)

# MIT XIII-A FUNCTIONAL SHIP SYNTHESIS MODEL

$hp \equiv \frac{33000 \cdot ft \cdot lbf}{min}$   $knt \equiv 1.69 \cdot \frac{ft}{sec}$   $mile \equiv knt \cdot hr$   $lton \equiv 2240 \cdot lb$   **SHIP NAME: DD13A**

**Seawater / Air propereties:**

$T_{SW} := 59$   $\rho_{SW} := 1.9905 \cdot \frac{slug}{ft^3}$   $\nu_{SW} := 1.2817 \cdot 10^{-5} \cdot \frac{ft^2}{sec}$   $\rho_A := .0023817 \cdot \frac{slug}{ft^3}$

**Designer input / acceptance of default values required for each yellow highlighted item.**

**Constraints requiring satisfaction and important comments are highlighted green.**

**This model also requires design parameter (DP) selection utilizing, and accounted for by, an integrated Excel spreadsheet. This Excel component is highlighted below. While satisfying each functional requirement (FR) a when prompted, access the speadsheet for DP definition by "double clicking" on the Excel Worksheet icon. Th spreadsheet is an interactive portion of this model. Prior to exiting the Excel component, update (save) for modifications to be incorporated.**

**Initial input values for $D_0$, $D_{10}$, $D_{20}$, and MAST are given in the $FR_6$ section only to allow proper functioning of Excel component. These values do not necessarily satisfy $FR_6$ and the decomposed child FRs. Therefore, actua values for these DPs must be input and verified to satisfy $FR_6$.**

$$\begin{bmatrix} W_x \\ A_x \\ CUM \end{bmatrix} :=$$

Worksheet

$$\begin{bmatrix} D_{0e} & D_{10e} & D_{20e} & MASTe \end{bmatrix}$$

## Customer Attributes:

**Sustained Speed:** $V_S := 28 \cdot knt$

**Endurance Speed:** $V_e := 20 \cdot knt$

**Range:** $E := 7500 \cdot mile$

**Stores period:** $T_S := 45 \cdot day$

**Manning:** **Determine manning/automation distribution using the functional allocation process by evaluatin lowest level FRs prior to satisfying design equations. Some parametrics based on manning numbers, as well as automated system characteristics, impose additional implications incorporat into this model.**

**Officers:** $N_O := 15$   **Enlisted:** **Chief Petty Officers:** $N_{CPO} := 20$

**Crewmembers:** $N_{CR} := 115$   $N_E := N_{CPO} + N_{CR}$

$N_E = 135$

## DD13A

| FR | DP (PAYLOAD NAME) | WT KEY | WT | VCG DATUM | VCG FT AD | AREA KEY | HULL FT2 | DKHS FT2 | CRUISE KW | BATTLE KW | WT MOMENT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.1 | NAVIGATION SYSTEM | W420 | 7.29 | 51.00 | 14.00 | A1132 | 0.00 | 848.30 | 55.99 | 53.50 | 473.85 |
| FR2 | **Cumulative DP2** | **WP FR2** | 7.29 | | | | 0.00 | 848.30 | 55.99 | 53.50 | |
| 3 | ADVANCED TOMAHAWK WEAPON CONTROL SYSTEM | W482 | 5.60 | 39.00 | -7.80 | NONE | 0.00 | 0.00 | 13.27 | 13.27 | 174.72 |
| 3 | COMBAT DF | W495 | 8.26 | 39.00 | 21.00 | A1141 | 0.00 | 448.00 | 15.47 | 19.34 | 495.60 |
| 3 | ELECTRONIC TEST & CHECKOUT | W499 | 1.10 | 43.05 | 10.80 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 59.24 |
| 3 | SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO | WF21 | 4.10 | 39.00 | -6.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 135.30 |
| FR3.x | **Cumulative DP3.x** | **WP FR3.x** | 19.06 | | | | 0.00 | 448.00 | 28.74 | 32.61 | |
| 3.1.1 | SPS-67 SURFACE SEARCH RADAR | W451 | 1.81 | 51.00 | -10.00 | A1121 | 0.00 | 70.00 | 8.00 | 0.00 | 74.21 |
| FR3.1.1 | **Cumulative DP3.1.1** | **WP FR3.1.1** | 1.81 | | | | 0.00 | 70.00 | 8.00 | 0.00 | |
| 3.1.2 | SQS-53C 5M BOW SONAR DOME ELEX W/MINE AVOIDANCE | W463 | 57.70 | 0.00 | 9.30 | A1122 | 1,942.00 | 0.00 | 39.00 | 39.00 | 536.61 |
| 3.1.2 | SSQ-61 BATHYTHERMOGRAPH | W465 | 0.31 | 37.14 | -10.90 | A1122 | 85.50 | 0.00 | 0.00 | 0.00 | 8.13 |
| 3.1.2 | SQQ-28 SONOBUOY PROCESSING SYSTEM | W466 | 5.26 | 51.00 | -44.86 | NONE | 0.00 | 0.00 | 1.15 | 1.15 | 32.30 |
| 3.1.2 | BATHYTHERMOGRAPH PROBES | WF29 | 0.21 | 37.14 | -6.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 6.54 |
| FR3.1.2 | **Cumulative DP3.1.2** | **WP FR3.1.2** | 63.48 | | | | 2,027.50 | 0.00 | 40.15 | 40.15 | |
| 3.1.3 | SPS-49(V)5 2-D AIR SEARCH RADAR | W452 | 9.03 | 51.00 | -7.10 | A1121 | 0.00 | 553.00 | 15.30 | 48.40 | 396.42 |
| 3.1.3 | X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL | W456 | 4.11 | 0.00 | 113.00 | NONE | 0.00 | 0.00 | 220.16 | 220.16 | 464.43 |
| 3.1.3 | 2X HARPOON SSM QUAD CANNISTER LAUNCHERS | W721 | 4.10 | 39.00 | 1.17 | A1220 | 0.00 | 0.00 | 0.00 | 1.60 | 164.70 |
| 3.1.3 | MK41 VLS 64-CELL | W721 | 107.72 | 38.07 | 1.14 | A1220 | 128.00 | 0.00 | 69.65 | 69.65 | 4,223.70 |
| 3.1.3 | HARPOON MISSILES – 8 RDS IN CANNISTERS | WF21 | 3.78 | 39.00 | 5.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 166.32 |
| 3.1.3 | MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS) | WF21 | 144.00 | 38.07 | 0.34 | A1220 | 1,420.00 | 720.00 | 0.00 | 0.00 | 5,531.04 |
| FR3.1.3 | **Cumulative DP3.1.3** | **WP FR3.1.3** | 272.74 | | | | 1,548.00 | 1,273.00 | 305.11 | 339.81 | |
| 3.1.4 | SLQ-32[V]3 ACTIVE ECM | W472 | 4.40 | 39.00 | 20.60 | NONE | 0.00 | 0.00 | 6.40 | 6.40 | 262.24 |
| FR3.1.4 | **Cumulative DP3.1.4** | **WP FR3.1.4** | 4.40 | | | | 0.00 | 0.00 | 6.40 | 6.40 | |
| 3.2.1 | MK XII AIMS IFF | W455 | 2.32 | 51.00 | -5.00 | NONE | 0.00 | 0.00 | 3.20 | 4.00 | 106.72 |
| FR3.2.1 | **Cumulative DP3.2.1** | **WP FR3.2.1** | 2.32 | | | | 0.00 | 0.00 | 3.20 | 4.00 | |
| 3.3 | VLS WEAPON CONTROL SYSTEM | W482 | 0.70 | 38.07 | 2.54 | A1220 | 56.00 | 310.00 | 13.62 | 19.69 | 28.43 |
| FR3.3 | **Cumulative DP3.3** | **WP FR3.3** | 0.70 | | | | 56.00 | 310.00 | 13.62 | 19.69 | |
| 3.3.2 | MK 86 5"/54 GFCS | W481 | 7.50 | 51.00 | -4.00 | A1212 | 0.00 | 168.00 | 6.00 | 15.40 | 352.50 |
| 3.3.2 | 1X MK45 5IN/54 GUN [ERGM) | W710 | 36.80 | 47.11 | -6.20 | A1210 | 270.00 | 0.00 | 36.18 | 37.88 | 1,505.34 |
| 3.3.2 | MK45 5IN ERGM AMMO - 600 RDS | WF21 | 35.10 | 47.11 | -28.40 | A1210 | 798.00 | 68.00 | 0.00 | 0.00 | 656.58 |
| FR3.3.2 | **Cumulative DP3.3.2** | **WP FR3.3.2** | 79.40 | | | | 1,068.00 | 236.00 | 42.18 | 53.28 | |
| 3.3.3 | ASW CONTROL SYSTEM [ASWCS] W/SSTD | W483 | 3.75 | 39.00 | -12.60 | A1240 | 320.00 | 0.00 | 8.61 | 8.61 | 99.00 |
| 3.3.3 | 2X MK32 SVTT ON DECK | W750 | 5.55 | 39.00 | 2.20 | A1244 | 0.00 | 368.00 | 2.00 | 5.00 | 228.66 |
| 3.3.3 | MK46 LWT ASW TORPEDOES – 6 RDS IN SVTT TUBES | WF21 | 1.36 | 39.00 | 2.50 | A1240 | 368.00 | 0.00 | 0.00 | 0.00 | 56.44 |
| FR3.3.3 | **Cumulative DP3.3.3** | **WP FR3.3.3** | 10.66 | | | | 688.00 | 368.00 | 10.61 | 13.61 | |
| 3.3.4 | MK92 MFCS - STIR/CORT/IADT/CEC | W482 | 6.29 | 51.00 | -1.40 | NONE | 0.00 | 0.00 | 50.30 | 85.80 | 311.98 |
| FR3.3.4 | **Cumulative DP3.3.4** | **WP FR3.3.4** | 6.29 | | | | 0.00 | 0.00 | 50.30 | 85.80 | |
| 3.4 | CIC W/UYQ-44 & 2X LSD | W410 | 19.34 | 0.00 | 35.58 | A1131 | 1,953.00 | 448.00 | 45.03 | 45.03 | 688.12 |
| 3.4 | ADVANCED DIGITAL C4I (JTIDS/LINK 16/LINK22/TADIXS/TACINTEL) | W440 | 37.91 | 51.00 | -46.84 | A1110 | 1,230.60 | 1,270.40 | 35.76 | 39.67 | 157.71 |
| FR3.4 | **Cumulative DP3.4** | **WP FR3.4** | 57.25 | | | | 3,183.60 | 1,718.40 | 80.79 | 84.70 | |
| 3.5 | LAMPS MKIII 18 X MK46 TORP & SONOBUOYS & PYRO | WF22 | 9.87 | 38.07 | 4.80 | A1374 | 0.00 | 588.00 | 0.00 | 0.00 | 423.13 |
| 3.5 | LAMPS MKIII 2 X SH-60B HELOS AND HANGAR (BASED) | WF23 | 12.73 | 38.07 | 4.50 | A1340 | 0.00 | 3,406.00 | 5.60 | 5.60 | 541.92 |
| 3.5 | LAMPS MKIII AVIATION SUPPORT AND SPARES | WF26 | 9.42 | 38.07 | 5.00 | A1390 | 357.00 | 0.00 | 0.00 | 0.00 | 405.72 |
| 3.5 | LAMPS MKIII:AVIATION FUEL [JP-5] | WF42 | 63.80 | 0.00 | 10.40 | A1380 | 0.00 | 0.00 | 0.00 | 0.00 | 663.52 |
| 3.5 | LAMPS MKIII AVIATION FUEL SYS | W542 | 4.86 | 38.07 | -11.00 | A1380 | 30.00 | 0.00 | 2.00 | 2.90 | 131.56 |
| 3.5 | LAMPS MKIII RAST/RAST CONTROL/HELO CONTROL | W588 | 31.10 | 38.07 | -1.60 | A1312 | 219.00 | 33.00 | 4.40 | 4.40 | 1,134.22 |
| 3.5 | LAMPS MKIII AVIATION SHOP AND OFFICE | W665 | 1.04 | 38.07 | -4.50 | A1360 | 194.00 | 75.00 | 0.00 | 0.00 | 34.91 |
| FR3.5 | **Cumulative DP3.5** | **WP FR3.5** | 132.82 | | | | 800.00 | 4,102.00 | 12.00 | 12.90 | |
| FR3 | **Cumulative DP3** | **WP FR3** | 650.93 | | | | 9,371.10 | 8,525.40 | 601.10 | 692.95 | |
| 4.1 | SLQ-32[V]3 - MK36 DLS W/6 LAUNCHERS | W474 | 0.96 | 39.00 | 5.39 | NONE | 0.00 | 0.00 | 2.40 | 2.40 | 42.61 |
| FR4.1 | **Cumulative DP4.1** | **WP FR5.1** | 0.96 | | | | 0.00 | 0.00 | 2.40 | 2.40 | |
| 4.2.1 | AN/SLQ-25A NIXIE | W473 | 0.24 | 37.14 | -6.20 | A1142 | 200.00 | 0.00 | 3.00 | 4.20 | 7.43 |
| FR4.2.1 | **Cumulative DP4.2.1** | **WP FR4.3.1** | 0.24 | | | | 200.00 | 0.00 | 3.00 | 4.20 | |
| 4.2.4 | MK36 DLS SRBOC CANNISTERS - 100 RDS | WF21 | 2.20 | 39.00 | 11.60 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 111.32 |
| FR4.2.4 | **Cumulative DP4.2.4** | **WP FR4.3.4** | 2.20 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| FR4 | **Cumulative DP4** | **WP FR4** | 3.40 | | | | 200.00 | 0.00 | 5.40 | 6.60 | |
| 5.1 | SQS-53C 5M BOW SONAR DOME HULL DAMPING | W636 | 6.70 | 0.00 | -2.50 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | -16.75 |
| FR5.1 | **Cumulative DP5.1** | **WP FR5.1** | 6.70 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| 5.4.1 | 64-CELL VLS MAGAZINE DEWATERING SYSTEM | W529 | 7.00 | 38.07 | -0.46 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 263.27 |
| FR5.4.1 | **Cumulative DP5.5.1** | **WP FR5.5.1** | 7.00 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| FR5 | **Cumulative DP5** | **W FR5** | 13.70 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| 6.1.2 | STEEL LANDING PAD [ON HULL] - SH-60 CAPABLE | W111 | 10.70 | 37.14 | 0.20 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 399.54 |
| 6.1.2 | 64 CELL VLS ARMOR - LEVEL III HY-80 | W164 | 28.00 | 43.05 | -10.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 925.48 |
| 6.1.2 | MK45 GUN HY-80 ARMOR LEVEL II | W164 | 9.00 | 47.11 | -8.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 351.95 |
| 6.1.2 | SQS-53C 5M BOW SONAR DOME W/MINE AVOIDANCE | W165 | 85.70 | 0.00 | -1.50 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | -128.55 |
| FR6 | **Cumulative DP6** | **WP FR6** | 133.40 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| | **GROUP WF20 (expendable ordnance)** | **WF20** | 222.77 | | | | 2,943.00 | 4,782.00 | | | |
| | **VARIABLE MILITARY PAYLOAD (WF20+WF42) (exp ord + helo fuel)** | **WVP** | 286.57 | | | | | | | | |
| | **ARMAMENT (WP500,WP600,W7,WF20)** | | | | | | 3,784.00 | 5,258.00 | | | |
| | ***TOTAL PAYLOAD*** | **WP** | 808.72 | | | | 9,571.10 | 9,373.70 | **KWP** 662.49 | 753.05 | 22,688.10 |

| | | | | | | |
|---|---|---|---|---|---|---|
| ***DATUM DEFINITIONS:*** | DEPTH0 | 50.58 | **WF20** | 222.77 | **WP** | 808.72 |
| | DEPTH3 | 47.11 | **WF23** | 12.73 | **WVP** | 286.57 |
| | DEPTH6.5 | 43.05 | **WF42** | 63.80 | **VCG P:** | 28.05 |
| | **DEPTH10** | 39.00 | | | **VCG VP:** | 30.35 |
| | DEPTH15 | 38.07 | **W164** | 37.00 | **KWP** | 662.49 |
| | **DEPTH20** | 37.14 | **W165** | 85.70 | | |
| | **BL** | 0.00 | **WP400** | 176.59 | **A HPC** | 5,787.10 |
| | **MAST BASE** | 51.00 | **WP500** | 42.96 | **A DPC** | 4,115.70 |
| | | | **WP600** | 7.74 | **A HPA** | 3,784.00 |
| | | | **W7** | 154.17 | **A DPA** | 5,258.00 |

**Total Manning:** $N_T := N_E + N_O$ $N_T = 150$

## $FR_1$ = <u>Move through water</u>

## $DP_1$ = <u>Propulsion system</u>

## Decomposition:

**Upper level FR and DP definitions given below**

**$FR_{1.1}$ = Produce propulsive power to achieve sustained speed**

**$DP_{1.1}$ = Main propulsion engines (MPE's)**

**Number and brake horsepower of propulsion engines:**

$N_{PENG} := 4$ $P_{BPENG} := 22750 \cdot hp$

**Propulsion Engines (PE) - GE LM2500-21's Contained in standard modules**

$L_{mod} := 26 \cdot ft$ $B_{mod} := 9 \cdot ft$ $H_{mod} := 10 \cdot ft$

$P_{IBRAKE} := N_{PENG} \cdot P_{BPENG}$ $P_{IBRAKE} = 91000 \circ hp$

$\eta := 0.97$ $P_I := \eta \cdot P_{IBRAKE}$ $P_I = 88270 \circ hp$

**$FR_{1.1.4}$ = Provide air to support engine combustion** **$DP_{1.1.4}$ = Engine inlet ducting**

**$FR_{1.1.5}$ = Remove combustion products** **$DP_{1.1.5}$ = Engine exhaust ducting**

**Inlet/exhaust Xsect area for PE:** $A_{IE} := 135.2 \cdot ft^2$ $A_{PIE} := N_{PENG} \cdot A_{IE}$ $A_{PIE} = 540.8 \circ ft^2$

**Deckhouse decks impacted by propulsion and generator inlet/exhaust:** $N_{DIE} := 2$

**Engine Inlet/Exhaust (Deckhouse) :** $A_{DIEP} := 1.4 \cdot N_{DIE} \cdot A_{PIE}$ $A_{DIEP} = 1514.24 \circ ft^2$

**Hull decks impacted by propulsion inlet/exhaust:** $N_{HPIE} := 0$

**Engine Inlet/Exhaust (Hull):** $A_{HIEP} := 1.4 \cdot N_{HPIE} \cdot A_{PIE}$ $A_{HIEP} = 0 \circ ft^2$

**$FR_{1.2}$ = Provide propulsive power at usable speed (rpm)** **$DP_{1.2}$ = Reduction gear**

**$FR_{1.2.2}$ = Cool reduction gear** **$DP_{1.2.2}$ = Lube oil system**

**LO weight:** $W_{F46} := 7.2 \cdot \text{lton}$ $\gamma_{LO} := 39 \cdot \dfrac{\text{ft}^3}{\text{lton}}$

**Allow for tank structure and expansion:** $V_{LO} := 1.02 \cdot 1.05 \cdot W_{F46} \cdot \gamma_{LO}$ $V_{LO} = 300.74 \, \text{ft}^3$

**$FR_{1.3}$ = Transfer power to water** **$DP_{1.3}$ = CRP propeller**

**Number of propellers:** $N_P := 0.50 \cdot N_{PENG}$ $N_P = 2$

**Select propeller diameter:** $D_P := 19 \cdot \text{ft}$

**Props:**
**(245)**

$$W_{PR} := 1.15 \cdot \left[ .05575 \cdot \text{lb} \cdot \left( \frac{D_P}{\text{ft}} \right)^{5.497 - \frac{0.0433}{\text{ft}} \cdot D_P} \cdot N_P \right] \qquad W_{PR} = 54.33 \, \text{lton}$$

**$FR_{1.3.1}$ = Receive speed (rpm) input from reduction gear** **$DP_{1.3.1}$ = Shaft**

**Select shaft length:** $L_S := 100 \cdot \text{ft}$ $N_S := N_P$

**Shafting:**
**(243)**

$$W_S := 1.15 \cdot \left( .356 \cdot \frac{\text{lton}}{\text{ft}} \cdot N_S \cdot L_S \right) \qquad W_S = 81.88 \, \text{lton}$$

**Total Shafting and Propellers:** $W_{ST} := W_S + W_{PR}$ $W_{ST} = 136.21 \, \text{lton}$

**$FR_{1.4}$ = Control speed and direction of movement locally** **$DP_{1.4}$ = Engineering operations station (EOS)**

**$FR_{1.5}$ = Control speed and direction of movement remotely** **$DP_{1.5}$ = Lee helm**

**Cumulative effects of above design decisions:**

**Propulsion:** $kW_P := .00466 \cdot \frac{kW}{hp} \cdot P_{IBRAKE}$ $\quad kW_P = 424.06 \bullet kW$

**Machinery Box (assumed near midships)**

$B_{MB} := 1.5 \cdot B_{mod} \cdot N_{PENG}$ $\quad L_{MB} := 1.5 \cdot L_{mod} \cdot N_S$ $\quad H_{MB} := 2.5 \cdot H_{mod}$

$B_{MB} = 54 \bullet ft$ $\quad L_{MB} = 78 \bullet ft$ $\quad H_{MB} = 25 \bullet ft$

**Machinery Box Area:** $A_{MB} := L_{MB} \cdot B_{MB}$ $\quad A_{MB} = 4212 \bullet ft^2$

**Machinery Box Volume:** $V_{MB} := H_{MB} \cdot A_{MB}$ $\quad V_{MB} = 105300 \bullet ft^3$

**Propulsion (200)**

**Basic Machinery:**
**(230+241/242+250-290)** $W_{BM} := P_I \cdot \frac{lb}{hp} \cdot \left[ 9.0 + 12.4 \cdot \left( P_I \cdot \frac{10^{-5}}{hp} - 1 \right)^2 \right]$ $\quad W_{BM} = 361.38 \bullet lton$

## $FR_2$ = Maintain desired course $\quad$ $DP_2$ = Maneuvering and control system

## Decomposition:

**Upper level FR and DP definitions given below**

**$FR_{2.1}$ = Determine if course is "safe"** $\quad$ **$DP_{2.1}$ = Navigation equipment**

*** Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with selected navigation system ($DP_{2.1}$) in Payload Spreadsheet**
**Note 1: VCG Datum and VCG normally do not require modification**
**Note 2: These parameters are utilized further at the appropriate stage of design definition**

**Input Bridge and Chartroom area:** $A_{DB} := 570 \cdot ft^2$

**Gyro/IC/Navigation (420, 430):** $W_{IC} := 43.8 \cdot lton$

$FR_{2.2}$ = Alter existing course $DP_{2.2}$ = Rudder

**Steering:** $kW_S := 78.7 \cdot kW$

$FR_{2.3}$ = Maneuver alongside pier $DP_{2.3}$ = Bow thrusters / APU's

**Aux Propulsion (APU):** $W_{237} := 0 \cdot lton$ $VCG_{237} := 0 \cdot ft$

**Fin Stabilizers:** (for one pair, electric power requirement = 50 kW) $kW_{fins} := 0 \cdot kW$

**Total Propulsion:** $W_2 := W_{BM} + W_{ST} + W_{237}$ (Cumulative $FR_1$ and $FR_{2.3}$)

$W_2 = 497.58 \cdot lton$

## $FR_3$ = Neutralize enemy targets $DP_3$ = Combat systems configuration

## Decomposition:

**Upper level FR and DP definitions given below**

* Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with all selected $DP_3$ and $DP_{3.X.X}$ systems in Payload Spreadsheet
Pertinent decomposition structure given in spreadsheet
Note 1: VCG Datum and VCG normally do not require modification
Note 2: These parameters are utilized further at the appropriate stage of design definition

$FR_{3.1}$ =Detect Targets $DP_{3.1}$ = Ship's sensors

$FR_{3.1.2}$ = Detect subsurface targets $DP_{3.1.2}$ = Sonar

$C_{SD} := 0.28$ SQS-53C Sonar: $A_{SD} := 215 \cdot ft^2$ (SQS-56: 27ft²; SQS-53C: 215ft²)

water: $W_{498} := 87.9 \cdot lton$ $VCG_{498} := -1.2 \cdot ft$

$FR_{3.2}$ = Classify targets $DP_{3.2}$ = Surveillance systems with identification protocols

$FR_{3.3}$ = Engage targets $DP_{3.3}$ = Weapons systems

$FR_{3.4}$ = Operate as "node" sharing information

$DP_{3.4}$ = Combat systems networking protocol

$FR_{3.5}$ = Provide target prosecution flexibility

$DP_{3.5}$ = Embarked helicopter

$N_{HELO} := 2$ (Use for $FR_{3.5}$ spreadsheet input)

**Helo's:** (Spreadsheet Output) $W_{F23} := W_{x_2} \cdot lton$ $W_{F23} = 12.73 \cdot lton$ ($FR_{3.5}$)

**Helo Fuel:** (Spreadsheet Output) $W_{F42} := W_{x_3} \cdot lton$ $W_{F42} = 63.8 \cdot lton$ ($FR_{3.5}$)

Allow for tank structure and expansion: $\gamma_{HF} := 43 \cdot \frac{ft^3}{lton}$ $V_{HF} := 1.02 \cdot 1.05 \cdot W_{F42} \cdot \gamma_{HF}$

**Cumulative effects of above design decisions:** $V_{HF} = 2938.18 \cdot ft^3$

**Payload Deck Area:** (Spreadsheet Output)

**Deckhouse:** Armament (W500, W600, W700, WF20): $A_{DPA} := A_{x_4} \cdot ft^2$ $A_{DPA} = 5258 \cdot ft^2$ (cumulative $FR_3$)

**Armament (all $W_{700}$):** (Spreadsheet Output) $W_7 := W_{x_{10}} \cdot lton$ $W_7 = 154.17 \cdot lton$ (cumulative $FR_3$)

## $FR_4$ = Protect from enemy attack

## $DP_4$ = Countermeasures methods

## Decomposition:

**Upper level FR and DP definitions given below**

* Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with selected $DP_{4.1}$ and $DP_{4.2.X}$ systems in Payload Spreadsheet
Note 1: VCG Datum and VCG normally do not require modification
Note 2: These parameters are utilized further at the appropriate stage of design definition

$FR_{4.1}$ = Neutralize enemy weapon's effect by "hard kill"

$DP_{4.1}$ = Self defense weapons

$FR_{4.2}$ = Neutralize enemy weapon's effect by "soft kill"

$DP_{4.2}$ = Self defense decoys

$FR_{4.2.1}$ = Neutralize acoustic targeted weapons

$DP_{4.2.1}$ = Deployable noisemakers (Nixie)

**Command and Surveillance Payload:** $W_{P400} := W_{x_7} \cdot lton$ **(cumulative $FR_3$, $FR_{4.1}$, and $FR_{4.2.1}$)**
**($W_{400}$ less 420 and 430)**
**(Spreadsheet Output)** $W_{P400} = 176.59 \cdot lton$

**Payload Deck Areas: (Spreadsheet Outputs)**

**Hull:** **C&D (W400):** $A_{HPC} := A_{x_1} \cdot ft^2$ **(cumulative $FR_{2.1}$, $FR_3$, $FR_{4.1}$, and $FR_{4.2.1}$)**

$A_{HPC} = 5787.1 \cdot ft^2$

**Deckhouse:** **C&D (W400):** $A_{DPC} := A_{x_2} \cdot ft^2$ **(cumulative $FR_{2.1}$, $FR_3$, $FR_{4.1}$, and $FR_{4.2.1}$)**

$A_{DPC} = 4115.7 \cdot ft^2$

**Deckhouse payload area:** $A_{DPR} := 1.15 \cdot A_{DPA} + 1.23 \cdot A_{DPC}$ $A_{DPR} = 11109.01 \cdot ft^2$
**(including access)**

**$FR_{4.2.4}$ = Neutralize home on target weapons** **$DP_{4.2.4}$ = Deployable false targets (Chaf)**

**Ordnance:** $W_{F20} := W_{x_1} \cdot lton$ $W_{F20} = 222.77 \cdot lton$ **(cumulative $FR_3$ and $FR_{4.2.4}$)**
**(incl helo wt, WF23)**
**(Spreadsheet Output)**

**Variable Payload:** $W_{VP} := CUM_2 \cdot lton$ $W_{VP} = 286.57 \cdot lton$ **(cumulative $FR_3$ and $FR_{4.2.4}$)**
**(Spreadsheet Output)**

**$FR_{4.3}$ = Reduce liklihood of enemy detection** **$DP_{4.3}$ = Signatures reduction**

**$FR_{4.3.2}$ = Reduce detection by EM sensing methods** **$DP_{4.3.2}$ = Exploitation of EM pulse characteristics**

**$FR_{4.3.2.1}$ = Minimize radar cross section (RCS)** **$DP_{4.3.2.1}$ = Superstructure construction**

**Living Deck Area:** $A_{COXO} := 225 \cdot ft^2$ $A_{DO} := 75 \cdot N_O \cdot ft^2$ $A_{DO} = 1125 \cdot ft^2$
**(Deckhouse)**

$A_{DL} := A_{COXO} + A_{DO}$ $A_{DL} = 1350 \cdot ft^2$

**Maintenance:** $A_{DM} := .05 \cdot (A_{DPR} + A_{DL})$ $A_{DM} = 622.95 \cdot ft^2$

**Assume inlet/exhaust Xsect area for PE is much greater than inlet/exhaust Xsect area for GE and deckhouse decks impacted by propulsion inlet/exhaust and generator inlet/exhaust are equal:**

$A_{DIEP} = 1514.24 \cdot ft^2$ $\quad A_{DIE} := 1.20 \cdot A_{DIEP}$ $\quad A_{DIE} = 1817.09 \cdot ft^2$

**Total Required Deckhouse Area and Volume:**

**Average deckhouse deck height:** $H_{DKd} := 9 \cdot ft$ $\quad H_{DK} := H_{DKd}$

$A_{DR} := A_{DPR} + A_{DL} + A_{DM} + A_{DB} + A_{DIE}$ $\quad A_{DR} = 15469.05 \cdot ft^2$

$V_{DR} := H_{DKd} \cdot A_{DR}$ $\quad V_{DR} = 139221.45 \cdot ft^3$

**Size Deck House:** **Must satisfy $C_{8.1}$: Available deckhouse volume > Required deckhouse volume**

**and $C_{9.1}$: Available arrangeable deckhouse area > Required arrangeable deckhouse area**

***** Set deckhouse volume ($V_D$) > or = to $V_{DR}$ / Therefore, $A_{DA}$ also > or = to $A_{DR}$**

$V_D := 156000\ ft^3$ $\quad V_D = 156000 \cdot ft^3$

$A_{DA} := \dfrac{V_D}{H_{DKd}}$ $\quad A_{DA} = 17333.33 \cdot ft^2$ $\quad A_{DR} = 15469.05 \cdot ft^2$

$C_{DHMAT} := 2$ **(Deckhouse Material: Aluminum - $C_{DHMAT} = 1$; Steel - $C_{DHMAT} = 2$)**

$\rho_{DH} := if(C_{DHMAT} = 1, 0.0007, 0.001429)$

**Deckhouse (150):** $W_{DH} := \rho_{DH} \cdot \dfrac{lton}{ft^3} \cdot V_D$ $\quad W_{DH} = 222.92 \cdot lton$

## $FR_5$ = Conduct sustained underway operations   $DP_5$ = Support / Auxiliary systems

## Decomposition:

**Upper level FR and DP definitions given below**

* **Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with all selected $DP_{5.1}$ and $DP_{5.4.1}$ systems in Payload Spreadsheet**
**Note 1: VCG Datum and VCG normally do not require modification**
**Note 2: These parameters are utilized further at the appropriate stage of design definition**

**$FR_{5.1}$ = Ensure habitable conditions**   **$DP_{5.1}$ = Crew support / habitability features**

**$FR_{5.1.1}$ = Supply stores (food) sufficient to feed the crew for stores period**   **$DP_{5.1.1}$ = Provisions loadout**

**Unrep and handling:** $kW_{RH} := 5.0 \cdot kW$

**Hull Stores** $A_{HS} := 300 \cdot ft^2 + .0158 \cdot \frac{ft^2}{lb} \cdot N_T \cdot 9 \cdot \frac{lb}{day} \cdot T_S$   $A_{HS} = 1259.85 \, ft^2$

**Provisions:** $W_{F31} := N_T \cdot 9 \cdot \frac{lb}{day} \cdot T_S$   $W_{F31} = 27.12 \, lton$

**General stores:** $W_{F32} := .0009598 \cdot \frac{lton}{day} \cdot T_S \cdot N_T$   $W_{F32} = 6.48 \, lton$

**$FR_{5.1.2}$ = Supply fresh water**   **$DP_{5.1.2}$ = Potable water system**

**Potable Water:**

**Water weight:** $W_{F52} := N_T \cdot .15 \cdot lton$   $W_{F52} = 22.5 \, lton$

**Allow for tank structure:** $\gamma_W := 36 \cdot \frac{ft^3}{lton}$

$V_W := 1.02 \cdot W_{F52} \cdot \gamma_W$   $V_W = 826.2 \, ft^3$

**distiller:** $Q_{DS} := 6.5 \cdot N_T + 250$

$FR_{5.1.3}$ = **Control climate for crew comfort and machinery operations**

$DP_{5.1.3}$ = **Climate control system**

**Heating:** $kW_H := .0013 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot \left[H_{DK} \cdot (4.0 \cdot A_{DR})\right]$ $\quad kW_H = 904.94 \circ kW$

**Ventilation:** $kW_{CPS} := .00026 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot \left[H_{DK} \cdot (4.0 \cdot A_{DR})\right]$ $\quad kW_{CPS} = 260.62 \circ kW$

**(zero if no CPS)**

$kW_V := .19 \cdot (kW_H + kW_P) + kW_{CPS}$ $\quad kW_V = 513.13 \circ kW$

**Air Conditioning:** $kW_{AC} := .67 \cdot \left[.1 \cdot kW \cdot N_T + \left(.0015 \cdot \frac{kW}{ft^3}\right) \cdot 1.3 \cdot \left[0.47 \cdot H_{DK} \cdot (4.0 \cdot A_{DR})\right] + .1 \cdot kW_P\right.$

$kW_{AC} = 380.42 \circ kW$

**Aux Boiler and FW:** $kW_B := .94 \cdot N_T \cdot kW$ $\quad kW_B = 141 \circ kW$
**(electric boiler)**

**aux steam (electric aux boiler): hotel steam:**

$Q_{HS} := 15 \cdot N_T$ $\quad W_{517} := .0013 \cdot (Q_{HS} + Q_{DS}) \cdot lton$ $\quad W_{517} = 4.52 \circ lton$

**CPS:** **($W_{CPS}$=30lton, CPS not installed = 0 lton)** $\quad W_{CPS} := 30 \cdot lton$

**environmental support:** $\quad W_{593} := 10 \cdot lton$

$FR_{5.1.4}$ = **Provide for crew hygiene**

$DP_{5.1.4}$ = **Plumbing system**

**Sewage:** $V_{SEW} := N_T \cdot 2 \cdot ft^3$ $\quad V_{SEW} = 300 \circ ft^3$

$FR_{5.1.5}$ = **Support feeding of crew**

$DP_{5.1.5}$ = **Food service equipment**

$FR_{5.1.6}$ = **Illuminate spaces**

$DP_{5.1.6}$ = **Lighting system**

**Lighting:** $kW_L := .0002053 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot \left[H_{DK} \cdot (4.0 \cdot A_{DR})\right]$ $\quad kW_L = 205.79 \circ kW$

**$FR_{5.1.7}$ = Allow crew escape when necessary** **$DP_{5.1.7}$ = Life boats**

**Mission outfit:** $W_{P600} := W_{x_9} \cdot lton$ $W_{P600} = 7.74 \cdot lton$ **($FR_{3.5}$ and $FR_{5.1}$)**
**(Spreadsheet Output)**

**$FR_{5.2}$ = Maintain equipment in operating condition** **$DP_{5.2}$ = Maintenance philosophy**

**Services and Work Spaces:** $kW_{SERV} := .35 \cdot N_T \cdot kW$ $kW_{SERV} = 52.5 \cdot kW$

**$FR_{5.3}$ = Communicate information** **$DP_{5.3}$ = Communications equipment**

**Masts:** $W_{171} := 2.0 \cdot lton$

**$FR_{5.4}$ = Combat damage** **$DP_{5.4}$ = Damage control (DC) systems**

**Mission handling/support:** $W_{P500} := W_{x_8} \cdot lton$ $W_{P500} = 42.96 \cdot lton$ **(cumulative $FR_5$)**
**(Spreadsheet Output)**

**Payload Deck Area:** **(Spreadsheet Output)**

**Hull:** **Armament (W500, W600, W700, WF20):** $A_{HPA} := A_{x_3} \cdot ft^2$ $A_{HPA} = 3784 \cdot ft^2$ **(cumulative $FR_3$ - $FR_5$)**

**Hull payload area:** $A_{HPR} := 1.15 \cdot A_{HPA} + 1.23 \cdot A_{HPC}$ $A_{HPR} = 11469.73 \cdot ft$
**(including access)**

**Payload Cruise Electric Power Requirement:** $kW_{PAY} := CUM_5 \cdot kW$
**(Spreadsheet Output)**

$kW_{PAY} = 662.49 \cdot kW$ **(cumulative $FR_2$ - $FR_5$)**

**Firemain:** $kW_F := .0001 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot \left[H_{DK} \cdot (4.0 \cdot A_{DR})\right]$ $kW_F = 100.24 \cdot kW$

**Waste Oil:** $V_{WASTE} := 1400 \cdot ft^3$

**$FR_{5.5}$ = Secure position while underway** **$DP_{5.5}$ = Anchoring system**

$FR_{5.6}$ = **Secure position while in port** $DP_{5.6}$ = **Mooring system**

**Note: Following equations primarily account for cumulative effects / Listed here since $FR_{5.6}$ is last FR prior to designing electrical system ($DP_{5.7}$)**

$V_{AUX} := 1.2 \cdot V_{MB}$ $\qquad V_{AUX} = 126360 \cdot ft^3$

**aux sys operating fluids:** $W_{598} := 60.5 \cdot lton$

$X := H_{DK} \cdot (6.0 \cdot A_{DR})$ $\qquad X = 835328.68 \cdot ft^3$ **(X approximates $V_T$)**

$$W_{AUX} := \left[ .000772 \cdot \left( \frac{X}{ft^3} \right)^{1.443} + 5.14 \cdot \frac{X}{ft^3} + 6.19 \cdot \left( \frac{X}{ft^3} \right)^{.7224} + 377 \cdot N_T + 2.74 \cdot \frac{P_I}{hp} \right] \cdot 10^{-4} \cdot lton + 113.8 \cdot lton$$

$W_{AUX} = 611.83 \cdot lton$

**environmental support:** $W_5 := W_{AUX} + W_{P500} + W_{517} + W_{593} + W_{598} + W_{CPS}$ $\qquad W_5 = 759.81 \cdot lton$

**Aux Machinery:** $kW_A := .22 \cdot N_T \cdot kW + kW_{fins}$ $\qquad kW_A = 33 \cdot kW$

**Miscellaneous:** $kW_M := 46.1 \cdot kW$

**Non-Payload Functional Load:**

$$kW_{NP} := kW_P + kW_S + kW_L + kW_M + kW_H + kW_V + kW_{AC} + kW_B + kW_F + kW_{RH} + kW_A + kW_{SER}$$

**Maximum Functional Load:**

$kW_{MFL} := kW_{PAY} + kW_{NP}$ $\qquad kW_{MFL} = 3547.37 \cdot kW$

**MFL with margins:**
**Required to satisfy $C_{10}$ = Incorporate design growth margins**

$kW_{MFLM} := 1.2 \cdot 1.2 \cdot kW_{MFL}$ $\qquad kW_{MFLM} = 5108.22 \cdot kW$

**24 hour electrical load:**

$$kW_{24} := .5\cdot(kW_{MFL} - kW_{P} - kW_{S}) + .8\cdot(kW_{P} + kW_{S}) \qquad kW_{24} = 1924.51\,kW$$

**with margin (design):** $kW_{24AVG} := 1.2\cdot kW_{24}$ $\qquad kW_{24AVG} = 2309.42\,kW$

$FR_{5.7}$ **= Provide electrical power** $\qquad DP_{5.7}$ **= Electrical system**

$FR_{5.7.1}$ **= Generate electrical power** $\qquad DP_{5.7.1}$ **= Ship's service generators**

**Ship Service Generators:** $N_G := 3$ $\qquad kW_G := 3000\cdot kW$ $\qquad$ **Generator Engines (GE) - DDA 501-k34's**

**Installed Electrical Power required per generator:**

$$kW_{GREQ} := \frac{kW_{MFLM}}{(N_G - 1)\cdot 0.9} \qquad kW_{GREQ} = 2837.9\,kW$$

$$kW_G = 3000\,kW$$

**Selection of generator type and quantity must satisfy $C_7$:**
**Installed electrical power > Required electrical power**

$$ERR_{KW} := \frac{kW_G - kW_{GREQ}}{kW_{GREQ}}$$

$$ERR_{KW} = 0.057$$

**Electrical Plant (300)** $\quad W_3 := 50\cdot lton + .03214\cdot\frac{lton}{kW}\cdot N_G\cdot kW_G \qquad W_3 = 339.26\,lton$

$FR_{5.7.1.1}$ **= Provide prime mover to turn rotor** $\qquad DP_{5.7.1.1}$ **= Generator engine**

$FR_{5.7.1.1.2}$ **= Provide fuel for continuous engine operation** $\qquad DP_{5.7.1.1.2}$ **= GE fuel system**

**Specific fuel rate for generator engines:** $FR_G := 0.288\cdot\frac{kg}{kW\cdot hr}$ $\qquad FR_G = 0.473\,\frac{lb}{hp\cdot hr}$

**Estimate Electric Fuel Rate:**

**Margin for instrumentation and machinery differences, $f(P_e/P_I)$:** $\quad f_{1e} := 1.04$

**Specified fuel rate:** $FR_{GSP} := f_{1e} \cdot FR_G$

**Average fuel rate allowing for plant deterioration:** $FR_{GAVG} := 1.05 \cdot FR_{GSP}$

$FR_{GAVG} = 0.69 \cdot \frac{lb}{kW \cdot hr}$ $\qquad$ $FR_{GAVG} = 0.52 \cdot \frac{lb}{hp \cdot hr}$

**$FR_{5.7.1.1.4}$ = Provide air to support engine combustion** $\qquad$ **$DP_{5.7.1.1.4}$ = Engine inlet ducting**

**$FR_{5.7.1.1.5}$ = Remove combustion products** $\qquad$ **$DP_{5.7.1.1.5}$ = Engine exhaust ducting**

**Inlet/exhaust X-sect area for gen:** $A_{GIE} := 38.4\ ft^2$ $\qquad$ $A_{eIE} := N_G \cdot A_{GIE}$

$A_{eIE} = 115.2 \cdot ft^2$

**Deckhouse decks impacted by propulsion and generator inlet/exhaust:** $N_{DIE} = 2$

**Engine Inlet/Exhaust (Deckhouse):** $A_{DIEe} := 1.4 \cdot N_{DIE} \cdot A_{eIE}$

$A_{DIEe} = 322.56 \cdot ft^2$

**Hull decks impacted by generator inlet/exhaust:** $N_{HeIE} := 1$

**Engine Inlet/Exhaust (Hull):** $A_{HIEe} := 1.4 \cdot N_{HeIE} \cdot A_{eIE}$ $\qquad$ $A_{HIEe} = 161.28 \cdot ft^2$

**$FR_{5.7.2}$ = Generate electrical power in emergency situation** $\qquad$ **$DP_{5.7.2}$ = Emergency diesel generator**

**$FR_{5.7.3}$ = Distribute electrical power** $\qquad$ **$DP_{5.7.3}$ = Electrical switchboards**

**$FR_{5.7.4}$ = Transport electrical power to equipment** $\qquad$ **$DP_{5.7.4}$ = Cabling**

$W_{CC} := .04 \cdot (W_{P400} + W_{IC})$ $\qquad$ $W_{CC} = 8.82 \cdot lton$

$W_4 := W_{P400} + W_{IC} + W_{CC} + W_{498}$ $\qquad$ $W_4 = 317.11 \cdot lton$

**$FR_{5.7.5}$ = Isolate equipment locally** $\qquad$ **$DP_{5.7.5}$ = Circuit breakers**

$FR_{5.8}$ = **Provide fuel source** $DP_{5.8}$ = **Fuel system**

**Burnable propulsion endurance fuel weight:** **Must satisfy $C_{12}$ = Carry adequate fuel to transit endurance range (E) at endurance speed ($V_e$) - Compliance verified after satisfying $FR_6$**

$$W_{BP} := 1980 \cdot \mathrm{lton}$$

**Tailpipe allowance and propulsion endurance fuel:** $TPA := .95$ **(shallow tanks)**

$$W_{FP} := \frac{W_{BP}}{TPA} \qquad W_{FP} = 2084.21 \cdot \mathrm{lton}$$

**Allow for expansion and tank structure in required propulsion tank volume:** $\gamma_F := 43 \cdot \frac{ft^3}{lton}$

$$V_{FP} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{FP} \qquad V_{FP} = 95984.15 \cdot ft^3$$

**Burnable electrical endurance fuel weight:**

$$W_{Be} := \frac{E}{V_e} \cdot \left(kW_{24AVG} \cdot FR_{GAVG}\right) \qquad W_{Be} = 268.06 \cdot \mathrm{lton}$$

**Tailpipe allowance and electrical endurance fuel:**

$$W_{Fe} := \frac{W_{Be}}{TPA} \qquad W_{Fe} = 282.17 \cdot \mathrm{lton}$$

**Allow for expansion and tank structure in required electrical fuel tank volume:**

$$V_{Fe} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{Fe} \qquad V_{Fe} = 12994.79 \cdot ft^3$$

**Total ship fuel: (DFM)**

$$W_{F41} := W_{FP} + W_{Fe} \qquad W_{F41} = 2366.38 \cdot \mathrm{lton}$$

$$V_F := V_{FP} + V_{Fe} \qquad V_F = 108978.94 \cdot ft^3$$

## $FR_6$ = Operate on surface of water $DP_6$ = Hull form

## Decomposition:

**Upper level FR and DP definitions given below**

**$FR_{6.1}$ = Enclose personnel and equipment** **$DP_{6.1}$ = Hull**

**$FR_{6.1.1}$ = Allow linear placement of equipment** **$DP_{6.1.1}$ = Hull extents**

**$FR_{6.1.1.1}$ = Facilitate longitudinal placement** **$DP_{6.1.1.1}$ = Length on design waterline**

**Input desired value:** $LWL := 501 \cdot ft$

**$FR_{6.1.1.2}$ = Facilitate transverse placement** **$DP_{6.1.1.2}$ = Beam**

**Input desired value (use beam at DWL):**
**Must satisfy $C_{13}$ = Contain machinery box beam** $B := 54 \cdot ft$ **> or =** $B_{MB} = 54 \cdot ft$

**Calculate Length to Beam Ratio and compare to historical monohull design trends given in Tables 1 - 4:** $C_{LB} := \frac{LWL}{B}$ $C_{LB} = 9.278$ **(7.5-10)**

**$FR_{6.1.2}$ = Allow verticle clearance for personnel and equipment** **$DP_{6.1.2}$ = Number of decks and average deck height**

**Number of hull decks:** $N_{decks} := 4$

**Average hull deck height:** $H_{DKh} := H_{DK}$ $H_{DKh} = 9 \cdot ft$

**$FR_{6.1.3}$ = Ensure watertight integrity** **$DP_{6.1.3}$ = Hull structure**

* **Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with all selected $DP_{6.1.3}$ systems in Payload Spreadsheet**
**Note 1: VCG Datum and VCG normally do not require modification**
**Note 2: These parameters are utilized further at the appropriate stage of design definition**

**$FR_{6.1.3.2}$ = Prevent water from entering over the sides** **$DP_{6.1.3.2}$ = Depth at Station 10 ($D_{10}$)**

**Must satisfy the following constraints simultaneously:**

**$C_{14}$ = Contain machinery box height**

**$C_{15}$ = $D_{10}$ must be > or = to $N_{decks}$*$H_{DK}$**

**$C_{16}$ = Longitudinal strength criteria**

$$M := \begin{bmatrix} H_{MB} \\ N_{decks} \cdot H_{DK} \\ \frac{LWL}{15} \end{bmatrix} \qquad M = \begin{bmatrix} 25 \\ 36 \\ 33.4 \end{bmatrix} \cdot ft \qquad D_{10MIN} := \max(M) \qquad D_{10MIN} = 36 \cdot ft$$

$$D_{10} = D_{10x} \qquad D_{10x} := 37.0 \cdot ft \qquad > \text{or} = \qquad D_{10MIN} = 36 \cdot ft$$

**Calculate Cubic Number (CN) :**

$$CN := \frac{LWL \cdot B \cdot D_{10x}}{10^5 \cdot ft^3} \qquad CN = 10.01$$

**$FR_{6.1.3.3}$ = Prevent water from entering through skin of ship**     **$DP_{6.1.3.3}$ = Exterior hull construction**

**Armor:** **(Spreadsheet Output)** $W_{164} := W_{x_5} \cdot lton$ $\quad W_{164} = 37 \cdot lton$ **($FR_{6.1.3}$)**

**Sonar Dome/Appendages (structure): (Spreadsheet Output)** $W_{165} := W_{x_6} \cdot lton$ $\quad W_{165} = 85.7 \cdot lton$ **($FR_{6.1.3}$)**

**Total Payload:** **(Spreadsheet Output)** $W_P := CUM_1 \cdot lton$ $\quad W_P = 808.72 \cdot lton$ **(cumulative $FR_2$ - $FR_6$)**

**Outfit & Furnishings (600)**

**Hull Fittings:** $W_{OFH} := 3.6 \cdot lton$

**Personnel-related:** $W_{OFP} := .8 \cdot (N_T - 9.5) \cdot lton$ $\quad W_{OFP} = 112.4 \cdot lton$

$$W_6 := W_{OFH} + W_{OFP} + W_{P600} \qquad W_6 = 123.74 \cdot \text{lton}$$

**Structure (100)**

**Hull Material: (OS: $C_{HMAT}$=1.0; HTS: $C_{HMAT}$=0.93)** $C_{HMAT} := 0.93$

**Hull (110-140, 160, 190):** $W_{BH} := C_{HMAT} \cdot \left(1.68341 \cdot CN^2 + 167.1721 \cdot CN - 103.283\right) \cdot \text{lto}$

$$W_{BH} = 1617.07 \cdot \text{lton}$$

**Foundations:** $W_{180} := .0675 \cdot W_{BM} + .072 \cdot \left(W_3 + W_4 + W_5 + W_7\right) \qquad W_{180} = 137.46 \cdot \text{lton}$

$$W_1 := W_{BH} + W_{DH} + W_{171} + W_{180} + W_{165} + W_{164} \qquad W_1 = 2102.15 \cdot \text{lton}$$

**Hull Living Deck Area:** $A_{HAB} := 50 \cdot \text{ft}^2 \quad A_{HL} := \left(A_{HAB} + \frac{LWL}{100} \cdot \text{ft}\right) \cdot N_T - A_{DL} \qquad A_{HL} = 6901.5 \cdot \text{ft}^2$

**Hull Ship Functions:** $A_{HSF} := 2500 \cdot \text{ft}^2 \cdot CN \qquad A_{HSF} = 25024.95 \cdot \text{ft}^2$

**Clean Balast ($V_{BAL}$ = 0 for compensated system):** $V_{BAL} := 0 \cdot \text{ft}^3$

**Total Tankage:** $V_{TK} := V_F + V_{HF} + V_{LO} + V_W + V_{SEW} + V_{WASTE} + V_{BAL} \quad V_{TK} = 114744.06 \cdot \text{ft}^3$

**Total Required Hull Area and Volume**

$$A_{HR} := A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + A_{HIEP} + A_{HIEe} \qquad A_{HR} = 44817.31 \cdot \text{ft}^2$$

$$V_{HR} := H_{DKh} \cdot A_{HR} \qquad V_{HR} = 403355.82 \cdot \text{ft}^3$$

**Total Required Area and Volume:**

$$A_{TR} := A_{HR} + A_{DR} \qquad A_{TR} = 60286.36 \cdot \text{ft}^2$$

$$V_{TR} := V_{DR} + V_{HR} \qquad V_{TR} = 542577.26 \cdot \text{ft}^3$$

*** Set available hull volume ($V_{HA}$) > or = to $V_{TR}$ - $V_D$ / Therefore, $A_{HA}$ also > or = to $A_{TR}$ - $A_{DA}$

$V_{HA} := V_{TR} - V_D$ $\qquad$ $V_{HA} = 386577.26 \cdot ft^3$

$A_{HA} := \dfrac{V_{HA}}{H_{DKh}}$ $\qquad$ $A_{HA} = 42953.03 \cdot ft^2$

| | | | |
|---|---|---|---|
| Must satisfy $C_8$: | Total available volume | > | Total required volume |
| and $C_9$: | Total available arrangeable area | > | Total required arrangeable area |

$V_{TA} := V_D + V_{HA}$ $\qquad$ $V_{TA} = 542577.26 \cdot ft^3$ $\quad > \quad$ $V_{TR} = 542577.26 \cdot ft^3$

$A_{TA} := A_{DA} + A_{HA}$ $\qquad$ $A_{TA} = 60286.36 \cdot ft^2$ $\quad > \quad$ $A_{TR} = 60286.36 \cdot ft^2$

$ERR_{VOL} := \dfrac{V_{TA} - V_{TR}}{V_{TR}}$ $\qquad$ $ERR_{VOL} = 0$ $\qquad$ $ERR_{AREA} := \dfrac{A_{TA} - A_{TR}}{A_{TR}}$ $\qquad$ $ERR_{AREA} = 0$

**Single Digit Weight Summary & Weight Balance:**

**Weight margin:**
**(Future Growth)** Required to satisfy $C_{10}$ = Incorporate design growth margins

$i1 := 1, 2 .. 7$ $\qquad$ $W_{M24} := 0.10 \cdot \left( \sum_{i1} W_{i1} \right)$ $\qquad$ $W_{M24} = 429.38 \cdot lton$

**Lightship:** $\qquad$ $W_{LS} := \sum_{i1} W_{i1} + W_{M24}$ $\qquad$ $W_{LS} = 4723.2 \cdot lton$

**Crew:** $\qquad$ $W_{F10} := 236 \cdot lb \cdot N_E + 400 \cdot lb \cdot (N_O + 1)$ $\qquad$ $W_{F10} = 17.08 \cdot lton$

$W_T := W_{LS} + W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10}$ $\qquad$ $W_T = 7456.53 \cdot lton$

**$FR_{6.2}$ = Support total ship weight** **$DP_{6.2}$ = Displaced hull form volume**

Must satisfy $C_3$: Full load displacement = Total weight

$W_{FL} := W_T$ $\Delta_{FL} := W_{FL}$ $\Delta_{FL} = 7456.53 \cdot \text{lton}$

**Calculate Displacement to Length Ratio and compare to historical monohull design trends*:**

$$C_{\Delta L} := \frac{\Delta_{FL}}{\left(\frac{LWL}{100}\right)^3} \qquad C_{\Delta L} = 59.3 \cdot \frac{\text{lton}}{\text{ft}^3} \qquad \textbf{(45-65)}$$

* **Reference: "Hydrodynamics in Ship Design" by Saunders, SNAME 1957 Vol II (pg 466)**

**Weight Balance:** $ERR_{WEIGHT} := \frac{\Delta_{FL} - W_T}{W_T}$ $ERR_{WEIGHT} = 0$

**Volume at LWL:** $V_{FL} := \Delta_{FL} \cdot 35 \cdot \frac{\text{ft}^3}{\text{lton}}$ $V_{FL} = 260978.67 \cdot \text{ft}^3$

**Underwater Hull Volume:** $V_{HUW} := V_{FL}$

**Above water Volume:** $V_{HAW} := V_{HR} - V_{FL}$ $V_{HAW} = 142377.14 \cdot \text{ft}^3$

**$FR_{6.2.1}$ = Maintain constant displacement** **$DP_{6.2.1}$ = Consistent loading philosophy**

**$FR_{6.2.2}$ = Maintain even transverse orientation (0 degree list)** **$DP_{6.2.2}$ = Centerline and symmetric (port/stbd) liquid tanks**

**$FR_{6.2.3}$ = Maintain even longitudinal orientation (0 trim)** **$DP_{6.2.3}$ = Longitudinal evenly spaced liquid tanks**

**$FR_{6.3}$ = Minimize total resistance**

**$DP_{6.3}$ = Hull form characteristics (coefficients of form)**

**Choose coefficient value within specified range*:**

$C_P := 0.610$ **(0.54 - 0.64)**

*** Reference: "Hydrodynamics in Ship Design" by Saunders, SNAME 1957 Vol II (pg 466)**

$C_W := .236 + .836 \cdot C_P$ $\qquad C_W = 0.746$

**$FR_{6.3.1}$ = Minimize residuary resistance**

**$DP_{6.3.1}$ = Hull form factors**

**$FR_{6.3.1.1}$ = Minimize resistance caused by hull "fullness"**

**$DP_{6.3.1.1}$ = Maximum section coefficient ($C_X$)**

**Choose coefficient value within specified range*:**

$C_X := 0.850$ **(0.70 - 0.85)**

*** Reference: "Hydrodynamics in Ship Design" by Saunders, SNAME 1957 Vol II (pg 469)**

$C_P = 0.61$

**$FR_{6.3.1.2}$ = Minimize resistance caused by underwater hull volume**

**$DP_{6.3.1.2}$ = Volumetric coefficient ($C_V$)**

$$C_V := \frac{V_{FL}}{LWL^3} \qquad C_V = 0.0021$$

**Constant draft required to satisfy $C_{11}$ = Always operate at DWL**

**Calculate Draft (LWL) and compare with historical monohull design trends given in Tables 1 - 4:**

$$T := \frac{V_{FL}}{C_P \cdot C_X \cdot LWL \cdot B} \qquad T = 18.6 \bullet ft \qquad C_{BT} := \frac{B}{T} \qquad C_{BT} = 2.902 \qquad \textbf{(2.8-3.7)}$$

**Must also satisfy sheer line criteria:**

**$C_{17}$ = Keep deck edge above water at 25 degree heel / Therefore, $D_{10SL}$ must be < or = $D_{10x}$**

$D_{10SL} := 0.21 \cdot B + T \qquad D_{10SL} = 29.94 \bullet ft \quad$ < or = $\quad D_{10x} = 37 \bullet ft$

**If $D_{10SL} > D_{10x}$, $D_{10min} = D_{10SL}$**
**If $D_{10SL} < D_{10x}$, $D_{10min} = D_{10x}$**

$$D_{0MIN} := 1.011827 \cdot T - 6.36215 \cdot \frac{10^{-6}}{ft} \cdot LWL^2 + 2.780649 \cdot 10^{-2} \cdot LWL + T \qquad D_{0MIN} = 49.76 \cdot ft$$

$$D_{20MIN} := .014 \cdot LWL \cdot \left(2.125 + 1.25 \cdot \frac{10^{-3}}{ft} \cdot LWL\right) + T \qquad D_{20MIN} = 37.9 \cdot ft$$

*** **Update to indicate design desires complying with indicated results (minimum values):** $D_{10x} = 37 \cdot ft$

| | | | |
|---|---|---|---|
| $D_{0e} \equiv 49.76$ | $D_{10e} \equiv 37.00$ | $D_{20e} \equiv 37.90$ | $MASTe \equiv 100.00$ |
| $D_0 := D_{0e} \cdot ft$ | $D_{10} := D_{10e} \cdot ft$ | $D_{20} := D_{20e} \cdot ft$ | $MAST := MASTe \cdot ft$ |

***** If $D_{10}$ not equal $D_{10x}$, must modify $DP_{6.1.3.2}$ (i.e., set $D_{10x} = D_{10}$)**

**$FR_{6.3.2}$ = Minimize friction resistance** | **$DP_{6.3.2}$ = Submerged hull / water interaction**

**$FR_{6.3.2.1}$ = Produce viscous resistance forces (drag)** | **$DP_{6.3.2.1}$ = Relative motion between submerged hull and wate**

**Use range of ship speeds for speed to length ratios ($R_i$), Reynold's numbers ($RN_i$), and ITTC friction ($RF_i$) :**

**CA's determine operating speed range:** **Ensure range includes $V_e$ and $V_S$ :**

$i := 1..7 \qquad V_i := i \cdot 5 \cdot knt \qquad V_4 := V_e \qquad V_6 := V_S$

$V_4 = 20 \cdot knt \qquad V_6 = 28 \cdot knt$

$$R_i := \frac{V_i}{\sqrt{LWL}} \qquad R_{N_i} := LWL \cdot \frac{V_i}{\nu_{SW}} \qquad C_{F_i} := \frac{.075}{\left(\log\left(R_{N_i}\right) - 2\right)^2}$$

$$V = \begin{bmatrix} 5 \\ 10 \\ 15 \\ 20 \\ 25 \\ 28 \\ 35 \end{bmatrix} \cdot knt \qquad R = \begin{bmatrix} 0.223 \\ 0.447 \\ 0.67 \\ 0.894 \\ 1.117 \\ 1.251 \\ 1.564 \end{bmatrix} \cdot \frac{knt}{\sqrt{ft}} \qquad R_N = \begin{bmatrix} 3.3 \cdot 10^8 \\ 6.61 \cdot 10^8 \\ 9.91 \cdot 10^8 \\ 1.32 \cdot 10^9 \\ 1.65 \cdot 10^9 \\ 1.85 \cdot 10^9 \\ 2.31 \cdot 10^9 \end{bmatrix} \qquad C_F = \begin{bmatrix} 0.0018 \\ 0.0016 \\ 0.0015 \\ 0.0015 \\ 0.0014 \\ 0.0014 \\ 0.0014 \end{bmatrix}$$

**$FR_{6.3.2.2}$ = Produce contact between hull and water** **$DP_{6.3.2.2}$ = Wetted surface area**

**Use Figure 7 with $C_P$ and $C_{BT}$ for TSS wetted surface coeficient:** $C_{STSS} := 2.536$

$C_P = 0.61 \qquad C_{BT} = 2.902$

$S_{TSS} := C_{STSS} \cdot (V_{FL})^{.5} \cdot LWL^{.5} \qquad S_{TSS} = 28998.17 \cdot ft^2$

**Specify or estimate actual ship surface area:** $S_S := S_{TSS}$

**Cumulative effects of above $FR_{6.3}$ design decisions:**

**Use Gertler* with $C_P$, $C_V$, $C_{BT}$, and $R_i$ to interpolate for $C_R$ and calcualte TSS resistance:**

$C_P = 0.61 \qquad C_V = 0.0021 \qquad C_{BT} = 2.902$

**$C_{BT}$=2.25** **$C_{BT}$=3.00** **$C_{BT}$=3.75**

$$R = \begin{bmatrix} 0.223 \\ 0.447 \\ 0.67 \\ 0.894 \\ 1.117 \\ 1.251 \\ 1.564 \end{bmatrix} \cdot \frac{knt}{\sqrt{ft}} \qquad C_{R2.25} := \begin{bmatrix} .00030 \\ .00030 \\ .00030 \\ .00063 \\ .00125 \\ .00259 \\ .00470 \end{bmatrix} \qquad C_{R3.00} := \begin{bmatrix} .00038 \\ .00038 \\ .00041 \\ .00087 \\ .00160 \\ .00279 \\ .00495 \end{bmatrix} \qquad C_{R3.75} := \begin{bmatrix} .00051 \\ .00051 \\ .00051 \\ .00086 \\ .00163 \\ .00295 \\ .00525 \end{bmatrix}$$

* **The Navy Department David W. Taylor Model Basin Report 806 of March 1954 - "A Reanalysis of the Original Test Data for the Taylor Standard Series" by Morton Goertler**
* **Reprinted in 1998 by the Society of Naval Architects and Marine Engineers (SNAME)**

**Form Factor:** $FF := \frac{4}{3}\cdot(C_{BT}-3)$ $\quad FF = -0.13$

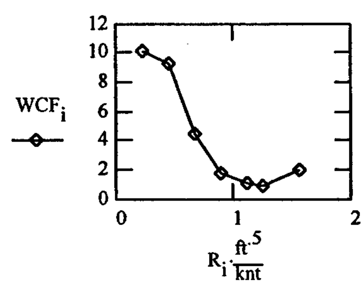
$$C_{RTSS_i} := C_{R3.00_i} + FF\cdot\left(\frac{C_{R3.75_i} - C_{R2.25_i}}{2}\right) + FF^2\cdot\left(\frac{C_{R2.25_i} + C_{R3.75_i}}{2} - C_{R3.00_i}\right)$$

$$C_{RTSS} = \begin{bmatrix} 0.0004 \\ 0.0004 \\ 0.0004 \\ 0.0009 \\ 0.0016 \\ 0.0028 \\ 0.0049 \end{bmatrix} \qquad R_{RTSS_i} := .5\cdot\left[\rho_{SW}\cdot S_S\cdot(V_i)^2\cdot C_{RTSS_i}\right] \qquad R_{RTSS} = \begin{bmatrix} 755.8 \\ 3023.22 \\ 7349.23 \\ 28122.33 \\ 81016.14 \\ 178765.93 \\ 496256.49 \end{bmatrix}\cdot lbf$$

**Worm Curve represents DD963 with bow mounted sonar dome:**

$$WCF_i := \left[67.31\cdot\left(R_i\cdot\frac{ft^{.5}}{knt}\right)^5 - 327.80\cdot\left(R_i\cdot\frac{ft^{.5}}{knt}\right)^4 + 604.33\cdot\left(R_i\cdot\frac{ft^{.5}}{knt}\right)^3 - 508.17\cdot\left(R_i\cdot\frac{ft^{.5}}{knt}\right)^2\right] + 175.28\cdot\left(R_i\cdot\frac{ft^{.5}}{knt}\right) - 9.$$

$$R = \begin{bmatrix} 0.223 \\ 0.447 \\ 0.67 \\ 0.894 \\ 1.117 \\ 1.251 \\ 1.564 \end{bmatrix}\cdot\frac{knt}{ft^{.5}} \qquad WCF = \begin{bmatrix} 10.16 \\ 9.32 \\ 4.52 \\ 1.82 \\ 1.14 \\ 0.95 \\ 2.03 \end{bmatrix}$$



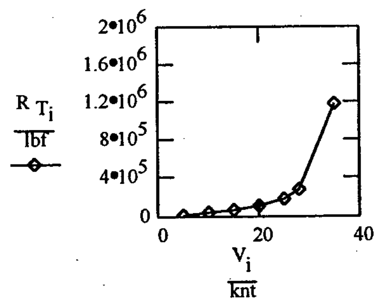
$$R_{R_i} := R_{RTSS_i} \cdot WCF_i \qquad R_R = \begin{bmatrix} 7682.37 \\ 28169.52 \\ 33216.63 \\ 51086.71 \\ 92611.56 \\ 169060.79 \\ 1.01 \cdot 10^6 \end{bmatrix} \cdot lbf$$

**Correlation Allowance:** $C_A := 0.0004$

$$R_{F_i} := .5 \cdot \left[ \rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot (C_A + C_{F_i}) \right] \qquad R_F = \begin{bmatrix} 4461.15 \\ 16588.71 \\ 35838.07 \\ 61954.78 \\ 94771.97 \\ 117626.06 \\ 180041.25 \end{bmatrix} \cdot lbf$$

**Calculate Bare Hull Ship Resistance:** $R_{T_i} := R_{F_i} + R_{R_i}$

$$R_T = \begin{bmatrix} 12143.52 \\ 44758.23 \\ 69054.69 \\ 113041.49 \\ 187383.52 \\ 286686.85 \\ 1.19 \cdot 10^6 \end{bmatrix} \cdot lbf$$




**$FR_{6.3.3}$ = Minimize air resistance** **$DP_{6.3.3}$ = Frontal area**

**Ship frontal area (+ 5% for masts, equipment, etc.):** $A_W := 1.05 \cdot B \cdot (D_{10} - T + 3 \cdot H_{DKd})$

$A_W = 2573.91 \cdot ft^2$

**Air Drag Coeficient:** $C_{AA} := 0.7$

**Must satisfy $C_4$ = Ensure intact stability (GM > 0 ft)**

**Must also satisfy $C_5$ = Maintain proper transverse dynamic stability (0.090 < GM/B < 0.122)**

**Stability**

**Payload VCG:** $VCG_P := CUM_3 \cdot ft$ $VCG_P = 32.22 \cdot ft$ **(cumulative $FR_2$ - $FR_6$)**

**Variable Payload VCG:** $VCG_{VP} := CUM_4 \cdot ft$ $VCG_{VP} = 29.75 \cdot ft$ **(cumulative $FR_3$ and $FR_6$**

**Calculate Light Ship Weight Group Moments:**

| Weight | VCG | | Product |
|---|---|---|---|
| $W_{BH} = 1617.07 \cdot lton$ | $VCG_1 := .527 \cdot D_{10}$ | $VCG_1 = 19.5 \cdot ft$ | $P_1 := W_{BH} \cdot VCG_1$ |
| $W_{DH} = 222.92 \cdot lton$ | $VCG_2 := D_{10} + 1.5 \cdot H_{DKd}$ | $VCG_2 = 50.5 \cdot ft$ | $P_2 := W_{DH} \cdot VCG_2$ |
| $W_{180} = 137.46 \cdot lton$ | $VCG_3 := .68 \cdot D_{10}$ | $VCG_3 = 25.16 \cdot ft$ | $P_3 := W_{180} \cdot VCG_3$ |
| $W_{171} = 2 \cdot lton$ | $VCG_4 := 2.65 \cdot D_{10}$ | $VCG_4 = 98.05 \cdot ft$ | $P_4 := W_{171} \cdot VCG_4$ |

$P_{100} := P_1 + P_2 + P_3 + P_4$ $VCG_{100} := \frac{P_{100}}{W_1}$ $VCG_{100} = 22.09 \cdot ft$

| | | | |
|---|---|---|---|
| $W_{BM} = 361.38 \cdot lton$ | $VCG_5 := .5 \cdot D_{10}$ | $VCG_5 = 18.5 \cdot ft$ | $P_5 := W_{BM} \cdot VCG_5$ |
| $W_{ST} = 136.21 \cdot lton$ | $VCG_6 := 3.9 \cdot ft + .19 \cdot T$ | $VCG_6 = 7.43 \cdot ft$ | $P_6 := W_{ST} \cdot VCG_6$ |
| $W_{237} = 0 \cdot lton$ | $VCG_7 := VCG_{237}$ | $VCG_7 = 0 \cdot ft$ | $P_7 := W_{237} \cdot VCG_7$ |

$P_{200} := P_5 + P_6 + P_7$ $VCG_{200} := \frac{P_{200}}{W_2}$ $VCG_{200} = 15.47 \cdot ft$

| | | | |
|---|---|---|---|
| $W_3 = 339.26 \cdot lton$ | $VCG_8 := .65 \cdot D_{10}$ | $VCG_8 = 24.05 \cdot ft$ | $P_8 := W_3 \cdot VCG_8$ |
| $W_{IC} = 43.8 \cdot lton$ | $VCG_9 := D_{10}$ | $VCG_9 = 37 \cdot ft$ | $P_9 := W_{IC} \cdot VCG_9$ |
| $W_{CC} = 8.82 \cdot lton$ | $VCG_{10} := .5 \cdot D_{10}$ | $VCG_{10} = 18.5 \cdot ft$ | $P_{10} := W_{CC} \cdot VCG_{10}$ |
| $W_{498} = 87.9 \cdot lton$ | $VCG_{11} := VCG_{498}$ | $VCG_{11} = -1.2 \cdot ft$ | $P_{11} := W_{498} \cdot VCG_{11}$ |

| | | | |
|---|---|---|---|
| $W_{AUX} = 611.83 \cdot \text{lton}$ | $VCG_{12} := .9 \cdot (D_{10} - 7.4 \cdot \text{ft})$ | $VCG_{12} = 26.64 \cdot \text{ft}$ | $P_{12} := W_{AUX} \cdot VCG_{12}$ |
| $W_{517} = 4.52 \cdot \text{lton}$ | $VCG_{13} := .5 \cdot H_{MB}$ | $VCG_{13} = 12.5 \cdot \text{ft}$ | $P_{13} := W_{517} \cdot VCG_{13}$ |
| $W_{OFH} = 3.6 \cdot \text{lton}$ | $VCG_{14} := .805 \cdot D_{10}$ | $VCG_{14} = 29.79 \cdot \text{ft}$ | $P_{14} := W_{OFH} \cdot VCG_{14}$ |
| $W_{OFP} = 112.4 \cdot \text{lton}$ | $VCG_{15} := 8 \cdot \text{ft} + .71 \cdot D_{10}$ | $VCG_{15} = 34.27 \cdot \text{ft}$ | $P_{15} := W_{OFP} \cdot VCG_{15}$ |

$ip := 1 .. 15$ $\quad P_{WG} := \sum_{ip} P_{ip} + W_P \cdot VCG_P - W_{VP} \cdot VCG_{VP}$ $\quad P_{WG} = 101826.11 \cdot \text{lton} \cdot \text{ft}$

**Light Ship KG**

$$VCG_{LS} := \frac{P_{WG}}{\sum_{i1} W_{i1}} \qquad VCG_{LS} = 23.71 \cdot \text{ft} \qquad KG_{LS} := VCG_{LS} \qquad KG_{LS} = 23.71 \cdot \text{ft}$$

**Calculate Variable Load Weight Group Moments:**

| Weight | VCG | | Product |
|---|---|---|---|
| $W_{F10} = 17.08 \cdot \text{lton}$ | $VCG_{16} := .746 \cdot D_{10}$ | $VCG_{16} = 27.6 \cdot \text{ft}$ | $P_{16} := W_{F10} \cdot VCG_{16}$ |
| $W_{F31} = 27.12 \cdot \text{lton}$ | $VCG_{17} := .55 \cdot D_{10}$ | $VCG_{17} = 20.35 \cdot \text{ft}$ | $P_{17} := W_{F31} \cdot VCG_{17}$ |
| $W_{F32} = 6.48 \cdot \text{lton}$ | $VCG_{18} := .65 \cdot D_{10}$ | $VCG_{18} = 24.05 \cdot \text{ft}$ | $P_{18}\ W_{F32} \cdot VCG_{18}$ |
| $W_{F41} = 2366.38 \cdot \text{lton}$ | $VCG_{19} := 7.5 \cdot \text{ft}$ | $VCG_{19} = 7.5 \cdot \text{ft}$ | $P_{19} := W_{F41} \cdot VCG_{19}$ |
| $W_{F42} = 63.8 \cdot \text{lton}$ | $VCG_{20} := 10. \cdot \text{ft}$ | $VCG_{20} = 10 \cdot \text{ft}$ | $P_{20} := W_{F42} \cdot VCG_{20}$ |
| $W_{F46} = 7.2 \cdot \text{lton}$ | $VCG_{21} := .35 \cdot D_{10}$ | $VCG_{21} = 12.95 \cdot \text{ft}$ | $P_{21} := W_{F46} \cdot VCG_{21}$ |
| $W_{F52} = 22.5 \cdot \text{lton}$ | $VCG_{22} := 7.5 \cdot \text{ft}$ | $VCG_{22} = 7.5 \cdot \text{ft}$ | $P_{22} := W_{F52} \cdot VCG_{22}$ |

$iL := 16 .. 22$ $\quad P_{WGL} := \sum_{iL} P_{iL} + W_{VP} \cdot VCG_{VP}$ $\quad P_{WGL} = 28195.96 \cdot \text{lton} \cdot \text{ft}$

$W_L := W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10}$ $\quad W_L = 2733.33 \cdot \text{lton}$

$$VCG_L := \frac{P_{WGL}}{W_L} \qquad VCG_L = 10.32 \cdot \text{ft}$$

**Calculate Ship Stability Characteristics:**

$KG_{MARG} := 0.5 \cdot ft$ **Required to satisfy $C_{10}$ = Incorporate design growth margins**

$$KG := \frac{W_{LS} \cdot KG_{LS} + W_L \cdot VCG_L}{W_T} + KG_{MARG} \qquad KG = 19.3 \cdot ft \qquad C_{IT} := -.497 + 1.44 \cdot C_W \qquad C_{IT} = 0.58$$

$$KB := \frac{T}{3} \cdot \left(2.5 - \frac{C_p \cdot C_X}{C_W}\right) \qquad KB = 11.19 \cdot ft \qquad BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}} \qquad BM = 14.54 \cdot ft$$

$GM := KB + BM - KG$ $\quad GM = 6.43 \cdot ft$ $\quad$ **(GM > 0 ft)**

$C_{GMB} := \frac{GM}{B}$ $\quad C_{GMB} = 0.119$ $\quad$ **(0.09 - 0.122)**

***** If GM < 0 ft and/or GM/B not within limits, must alter DPs satisfying $FR_6$ and associated children (LWL, B, $C_p$, $C_x$, $D_0$, $D_{10}$, $D_{20}$) until achieve $C_4$ and $C_5$ compliance**

**- If stated DPs modified, must additionally verify/re-achieve $C_8$, $C_9$, and $C_{13}$ - $C_{17}$**

**Calculate roll period:**

$C := \frac{0.38 + 0.55}{2} \cdot ft^{-0.5}$ **(C = empirical constant = 0.38 - 0.55)** $\quad T_{roll} := \frac{C \cdot B}{\sqrt{GM}} \cdot sec$ $\quad T_{roll} = 9.9 \cdot sec$

**Must satisfy $C_6$: Installed propulsive power ≥ Required propulsive power**

**- Verify propulsion system capable of achieving sustained speed**

**Determine total required propulsive power:**

**hull:** $\quad P_{EBH_i} := R_{T_i} \cdot V_i$

$$P_{EBH} = \begin{bmatrix} 186.57 \\ 1375.3 \\ 3182.79 \\ 6946.91 \\ 14394.46 \\ 24665.49 \\ 127469.11 \end{bmatrix} \cdot hp$$

**Use Figure 8 or 9 with LWL for Appendage Drag Coeficient:** $C_{DAPP} := 2.75 \cdot \frac{hp \cdot 10^{-5}}{ft^2 \cdot knt^3}$

$LWL = 501 \cdot ft$

**appendage (propellers):** $P_{EAPPp_i} := \left[ \left( LWL \cdot D_P \right) \cdot C_{DAPP} \right] \cdot \left( V_i \right)^3$

$$P_{EAPPp} = \begin{bmatrix} 32.72 \\ 261.77 \\ 883.48 \\ 2094.18 \\ 4090.2 \\ 5746.43 \\ 11223.5 \end{bmatrix} \cdot hp$$

**appendage (sonar dome):** $P_{EAPPsd_i} := \left( .5 \cdot C_{SD} \cdot \rho_{SW} \cdot A_{SD} \right) \cdot \left( V_i \right)^3$

$$P_{EAPPsd} = \begin{bmatrix} 65.73 \\ 525.81 \\ 1774.6 \\ 4206.45 \\ 8215.73 \\ 11542.51 \\ 22543.96 \end{bmatrix} \cdot hp$$

**total appendage:** $P_{EAPP_i} := P_{EAPPp_i} + P_{EAPPsd_i}$

$$P_{EAPP} = \begin{bmatrix} 98.45 \\ 787.58 \\ 2658.08 \\ 6300.63 \\ 12305.92 \\ 17288.94 \\ 33767.46 \end{bmatrix} \cdot hp$$

**air:** $P_{EAA_i} := .5 \cdot C_{AA} \cdot A_W \cdot \rho_A \cdot \left( V_i \right)^3$

$$P_{EAA} = \begin{bmatrix} 2.35 \\ 18.83 \\ 63.55 \\ 150.64 \\ 294.22 \\ 413.35 \\ 807.33 \end{bmatrix} \cdot hp$$

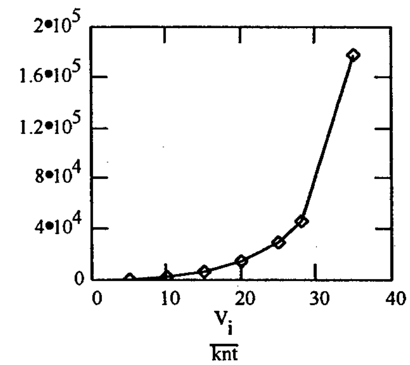
**Total Ship Effective Horsepower:**

$$P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i} \qquad P_{ET} = \begin{bmatrix} 287.37 \\ 2181.71 \\ 5904.42 \\ 13398.19 \\ 26994.6 \\ 42367.78 \\ 162043.9 \end{bmatrix} \circ hp$$

**Power Margin Factor (margin for concept design = 10%):**
**Required to satisfy $C_{10}$ = Incorporate design growth margins**

$$PMF := 1.10 \qquad EHP_i := PMF \cdot P_{ET_i}$$

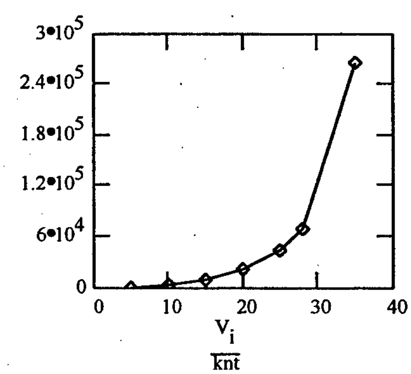
$$V = \begin{bmatrix} 5 \\ 10 \\ 15 \\ 20 \\ 25 \\ 28 \\ 35 \end{bmatrix} \circ knt \qquad EHP = \begin{bmatrix} 316.11 \\ 2399.88 \\ 6494.87 \\ 14738 \\ 29694.06 \\ 46604.56 \\ 178248.28 \end{bmatrix} \circ hp$$




**Required Shaft Horsepower:**

**Approximate Propulsive Coeficient (PC):** $PC := 0.67$ $\qquad SHP_i := \dfrac{EHP_i}{PC}$

$$SHP = \begin{bmatrix} 471.8 \\ 3581.91 \\ 9693.83 \\ 21997.02 \\ 44319.5 \\ 69559.05 \\ 266042.22 \end{bmatrix} \circ hp$$




**Sustained Shaft Horsepower:** $P_S := SHP_6$ $\qquad P_S = 69559.05 \circ hp$

**Installed Shaft Horsepower required to achieve sustained speed (Allows for fouling and sea state) :**

$P_{IREQ} := 1.25 \cdot P_S$  $P_{IREQ} = 86948.81 \, hp$  $P_I = 88270 \, hp$  **($P_I$ must be > $P_{IREQ}$)**

$$ERR_{POWER} := \frac{P_I - P_{IREQ}}{P_{IREQ}}$$

$ERR_{POWER} = 0.015$

***** If $P_I < P_{IREQ}$ ($ERR_{POWER} < 0$), must alter DPs satisfying $FR_6$ and associated children (LWL, B, $C_p$, $C_x$, $D_0$, $D_{10}$, $D_{20}$) until achieve $C_6$ compliance**

**- If stated DPs modified, must additionally verify/re-achieve $C_4$, $C_5$, $C_8$, $C_9$, and $C_{13}$ - $C_{17}$ compliance**

**Must satisfy $C_{17}$ = Carry adequate fuel to transit endurance range (E) at endurance speed ($V_e$), i.e. $E_{act}$ >=**

$P_e := SHP_4$  $P_e = 21997.02 \, hp$  $P_{eBAVG} := 1.1 \cdot \frac{P_e}{\eta}$  $P_{eBAVG} = 24945.07 \, hp$

**Specific fuel rate for propulsion engines:**  $FR := 1.97 \cdot \frac{lb}{hp^{.85} \cdot hr} \cdot P_{eBAVG}^{-.15}$  $FR = 0.431 \, \frac{lb}{hp \cdot hr}$

**(FR for GT = calc; FR for diesel = 0.327 lb/hphr; FR for ICR = 0.347 lb/hphr)**

**Margin for instrumentation and machinery differences, f($P_e$/$P_I$):** $f_1 := 1.04$

**Specified fuel rate:**  $FR_{SP} := f_1 \cdot FR$

**Average fuel rate allowing for plant deterioration:**  $FR_{AVG} := 1.05 \cdot FR_{SP}$  $FR_{AVG} = 0.47 \, \frac{lb}{hp \cdot hr}$

$$E_{act} := \frac{W_{BP} \cdot V_e}{\left(P_{eBAVG} \cdot FR_{AVG}\right)}$$

$E_{act} = 7547.75 \, mile$  **> or =**  $E = 7500 \, mile$

$W_{BP} = 1980 \, lton$

***** If $E_{act}$ < E, increase $W_{BP}$ (weigth of burnable propulsion fuel)**

***** If $E_{act}$ >> E, decrease $W_{BP}$ (only if desired)**

**- If $W_{BP}$ modified, must additionally verify/re-achieve $C_4$ - $C_6$, $C_8$, $C_9$, and $C_{13}$ - $C_{17}$ compliance**

***** Strict adherence to Axiomatic Design principles does not allow modification of $W_{BP}$ ($DP_{5.8}$)**

## CONCEPT DESIGN PARAMETERS AND CONVERGENCE VERIFICATION:

**GROSS CHARACTERISTICS:** **Parameter/ratio ranges are ship specific - Compare with respective monohul design lanes**

| | | | | | |
|---|---|---|---|---|---|
| $C_P = 0.61$ | **(0.54 - 0.64)** | $C_{\Delta L} = 59.3 \cdot \frac{\text{lton}}{\text{ft}^3}$ | **(45 - 65)** | $LWL = 501 \cdot \text{ft}$ |
| $C_X = 0.85$ | **(0.70 - .85)** | $C_V = 0.0021$ | | $B = 54 \cdot \text{ft}$ |
| $C_{BT} = 2.902$ | **(2.8 - 3.7)** | $C_{LB} = 9.278$ | **(7.5 - 10)** | $T = 18.6 \cdot \text{ft}$ |

**ENERGY BALANCE:**

| | | | |
|---|---|---|---|
| $V_S = 28 \cdot \text{knt}$ | $P_I = 88270 \cdot \text{hp}$ | $P_{IREQ} = 86948.81 \cdot \text{hp}$ | $ERR_{POWER} = 0.015$ |
| $V_e = 20 \cdot \text{knt}$ | $kW_G = 3000 \cdot \text{kW}$ | $kW_{GREQ} = 2837.9 \cdot \text{kW}$ | $ERR_{KW} = 0.057$ |
| $E_{act} = 7547.75 \cdot \text{mile}$ | | | |

**AREA/VOLUME BALANCE:**

| | | | |
|---|---|---|---|
| $A_{TR} = 60286.36 \cdot \text{ft}^2$ | $A_{HR} = 44817.31 \cdot \text{ft}^2$ | $A_{DR} = 15469.05 \cdot \text{ft}^2$ | |
| $A_{TA} = 60286.36 \cdot \text{ft}^2$ | $A_{HA} = 42953.03 \cdot \text{ft}^2$ | $A_{DA} = 17333.33 \cdot \text{ft}^2$ | $ERR_{AREA} = 0$ |
| $V_{TR} = 542577.26 \cdot \text{ft}^3$ | $V_{HR} = 403355.82 \cdot \text{ft}^3$ | $V_{DR} = 139221.45 \cdot \text{ft}^3$ | |
| $V_{TA} = 542577.26 \cdot \text{ft}^3$ | $V_{HA} = 386577.26 \cdot \text{ft}^3$ | $V_D = 156000 \cdot \text{ft}^3$ | $ERR_{VOL} = 0$ |
| $V_{MB} = 105300 \cdot \text{ft}^3$ | $V_{AUX} = 126360 \cdot \text{ft}^3$ | $V_{TK} = 114744.06 \cdot \text{ft}^3$ | $D_{10} = 37 \cdot \text{ft}$ |

**WEIGHT BALANCE:**

| | | | |
|---|---|---|---|
| $W_{FL} = 7456.53 \cdot \text{lton}$ | $W_T = 7456.53 \cdot \text{lton}$ | $ERR_{WEIGHT} = 0$ | |
| $W_1 = 2102.15 \cdot \text{lton}$ | $W_4 = 317.11 \cdot \text{lton}$ | $W_7 = 154.17 \cdot \text{lton}$ | $W_{LS} = 4723.2 \cdot \text{lton}$ |
| $W_2 = 497.58 \cdot \text{lton}$ | $W_5 = 759.81 \cdot \text{lton}$ | $W_{F41} = 2366.38 \cdot \text{lton}$ | $W_P = 808.72 \cdot \text{lton}$ |
| $W_3 = 339.26 \cdot \text{lton}$ | $W_6 = 123.74 \cdot \text{lton}$ | | |

**STABILITY/PAYLOAD:** $C_{GMB} = 0.119$ **(0.09 - 0.122)** $F_P := \frac{W_P}{W_{FL}}$ $F_P = 0.108$

# SIMPLIFIED COST MODEL

**DD13A**

**Definitions (units):**

$\text{Mdol} := \text{coul}$ $\quad \text{Bdol} := 1000\cdot\text{Mdol}$ $\quad \text{Kdol} := \frac{\text{Mdol}}{1000}$ $\quad \text{dol} := \frac{\text{Kdol}}{1000}$

$\text{lton} := 2240\cdot\text{lb}$ $\quad \text{hp} := \frac{33000\cdot\text{ft}\cdot\text{lbf}}{\text{min}}$

## 1. Single Digit Weight Summary:

$i1 := 100, 200 .. 700$

$W_{100} := W_1$ $\quad W_{400} := W_4$ $\quad W_{500} := W_5$ $\quad W_{F_{20}} := W_{F20}$ $\quad W_{F_{20}} = 222.77 \cdot \text{lton}$ #

$W_{IC} = 43.8 \cdot \text{lton}$ #

$W_{200} := W_2$ $\quad W_{600} := W_6$ $\quad W_{F_{23}} := W_{F23}$ $\quad W_{F_{23}} = 12.73 \cdot \text{lton}$

#

$W_{300} := W_3$ $\quad W_{700} := W_7$

#

**Weight margin:** $W_M := W_{M24}$ $\quad W_M = 429.38 \cdot \text{lton}$

## 2. Additional Characteristics:

**Lightship:**

$W_{LS} := \sum_{i1} W_{i1} + W_M$ $\quad W_{LS} = 4723.2 \cdot \text{lton}$

**Costed Military Payload: (helo and helo fuel weight not included)**

$W_{MP} := \left[\left(W_{400} + W_{700}\right) - W_{IC}\right] + W_{F_{20}} - W_{F_{23}}$ $\quad W_{MP} = 637.52 \cdot \text{lton}$

**Installed Propulsion Power:** $P_I = 88270 \cdot \text{hp}$ $\quad P_{SUM} := P_I$ #

**Manning: (crew + air detachment + staff)**

**Officers:** $N_{C_1} := N_O$ $\quad$ **CPO's:** $N_{C_2} := N_{CPO}$ $\quad$ **Crewmembers:** $N_{C_3} := N_{CR}$ #

$N_{C_1} = 15$ $\quad N_{C_2} = 20$ $\quad N_{C_3} = 115$

**Ship Service Life:** $L_S := 30$ $\quad$ **Initial Operational Capability:** $Y_{IOC} := 2010$ #

**Total Ship Acquisition:** $N_S := 20$ $\quad$ **Production Rate (per year):** $R_P := 3$ #

## 3. Inflation:

**Base Year:** $Y_B := 2000$ $\quad iy := 1 .. Y_B - 1981$ #

**Average Inflation Rate (%):** $R_I := 3.0$ #
**(from 1981)**

$$F_I := \prod_{iy} \left(1 + \frac{R_I}{100}\right) \qquad F_I = 1.75$$

## 4. Lead Ship Cost:

*a. Lead Ship Cost - Shipbuilder Portion:*

**SWBS costs: (See Enclosure 1 for $K_N$ factors); includes escalation estimate**

**Structure** $\quad K_{N1} := \frac{.55 \cdot Mdol}{lton^{.772}} \quad C_{L_{100}} := .03395 \cdot F_I \cdot K_{N1} \cdot (W_{100})^{.772} \quad C_{L_{100}} = 12.03 \cdot Mdol$

**+ Propulsion** $\quad K_{N2} := \frac{1.2 \cdot Mdol}{hp^{.808}} \quad C_{L_{200}} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{SUM}^{.808} \quad C_{L_{200}} = 38.8 \cdot Mdol$

**+ Electric** $\quad K_{N3} := \frac{1.0 \cdot Mdol}{lton^{.91}} \quad C_{L_{300}} := .07505 \cdot F_I \cdot K_{N3} \cdot (W_{300})^{.91} \quad C_{L_{300}} = 26.43 \cdot Mdol$

**+ Command, Control, Surveillance**

$K_{N4} := \frac{2.0 \cdot Mdol}{lton^{.617}} \quad C_{L_{400}} := .10857 \cdot F_I \cdot K_{N4} \cdot (W_{400})^{.617} \quad C_{L_{400}} = 13.3 \cdot Mdol$

**(less payload GFM cost)**

**+ Auxiliary** $\quad K_{N5} := \frac{1.5 \cdot Mdol}{lton^{.782}} \quad C_{L_{500}} := .09487 \cdot F_I \cdot K_{N5} \cdot (W_{500})^{.782} \quad C_{L_{500}} = 44.65 \cdot Mdol$

**+ Outfit** $\quad K_{N6} := \frac{1.0 \cdot Mdol}{lton^{.784}} \quad C_{L_{600}} := .09859 \cdot F_I \cdot K_{N6} \cdot (W_{600})^{.784} \quad C_{L_{600}} = 7.56 \cdot Mdol$

**+ Armament** $\quad K_{N7} := \frac{1.0 \cdot Mdol}{lton^{.987}} \quad C_{L_{700}} := .00838 \cdot F_I \cdot K_{N7} \cdot (W_{700})^{.987} \quad C_{L_{700}} = 2.12 \cdot Mdol$

**(Less payload GFM cost)**

**+ Margin Cost:**

$$C_{LM} := \frac{W_M}{\left(W_{LS} - W_M\right)} \cdot \left(\sum_{i1} C_{L_{i1}}\right) \qquad C_{LM} = 14.49 \cdot \text{Mdol}$$

**+ Integration/Engineering: (Lead ship includes detail design engineering + plans for class)**

$$K_{N8} := \frac{10.\cdot \text{Mdol}}{\text{Mdol}^{1.099}} \qquad C_{L_{800}} := .034 \cdot K_{N8} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{1.099} \qquad C_{L_{800}} = 89.52 \cdot \text{Mdol}$$

**+ Ship Assembly + Support: (Lead ship includes all tooling, jigs, special facilities for class)**

$$K_{N9} := \frac{2.0 \cdot \text{Mdol}}{(\text{Mdol})^{.839}} \qquad C_{L_{900}} := .135 \cdot K_{N9} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{.839} \qquad C_{L_{900}} = 19.02 \cdot \text{Mdol}$$

***a. Lead Ship Cost - Shipbuilder Portion (continued):***

**= <u>Total Lead Ship Construction Cost: (BCC)</u>:**

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_{800}} + C_{L_{900}} + C_{LM} \qquad C_{LCC} = 267.91 \cdot \text{Mdol}$$

**+ Profit:**

$$F_P := .10 \qquad C_{LP} := F_P \cdot C_{LCC} \qquad C_{LP} = 26.79 \cdot \text{Mdol}$$ #

**= <u>Lead Ship Price</u>:**

$$P_L := C_{LCC} + C_{LP} \qquad P_L = 294.71 \cdot \text{Mdol}$$

**+ Change Orders:**

$$C_{LCORD} := .12 \cdot P_L \qquad C_{LCORD} = 35.36 \cdot \text{Mdol}$$ #

**= *<u>Total Shipbuilder Portion:</u>***

$$C_{SB} := P_L + C_{LCORD} \qquad C_{SB} = 330.07 \cdot \text{Mdol}$$

### *b. Lead Ship Cost - Government Portion*

**Other support:** $C_{LOTH} := .025 \cdot P_L$ $\quad C_{LOTH} = 7.37 \cdot Mdol$ #

**+ Program Manager's Growth:** $C_{LPMG} := .1 \cdot P_L$ $\quad C_{LPMG} = 29.47 \cdot Mdol$ #

**+ Ordnance and Electrical GFE:**
**(Military Payload GFE)**

$$C_{LMPG} := \left(.318 \cdot \frac{Mdol}{lton} \cdot W_{MP} + N_{HELO} \cdot 18.71 \cdot Mdol\right) \cdot F_I$$

$C_{LMPG} = 421.1 \cdot Mdol$ **(or incl actual cost if known)**

**+ HM&E GFE (boats, IC):** $C_{LHMEG} := .02 \cdot P_L$ $\quad C_{LHMEG} = 5.89 \cdot Mdol$

**+ Outfittimg Cost :** $C_{LOUT} := .04 \cdot P_L$ $\quad C_{LOUT} = 11.79 \cdot Mdol$

= ***Total Government Portion:***

$$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT} \qquad C_{LGOV} = 475.62 \cdot Mdol$$

### *c. Total Lead Ship End Cost:* ***(Must always be less than appropriation)***

* ***Total End Cost:*** $C_{LEND} := C_{SB} + C_{LGOV}$ $\quad C_{LEND} = 805.69 \cdot Mdol$

### d. Total Lead Ship Acquisition Cost:

**+ Post-Delivery Cost (PSA):** $C_{LPDEL} := .05 \cdot P_L$ $\quad C_{LPDEL} = 14.74 \cdot Mdol$ #

= **Total Lead Ship Acquisition Cost:** $C_{LA} := C_{LEND} + C_{LPDEL}$ $\quad C_{LA} = 820.43 \cdot Mdol$

## 5. Follow-Ship Cost:

**Learning Rate/Factor:** $R_L := .97$ $\quad F := 2 \cdot R_L - 1$ $\quad F = 0.94$ #

***a. Follow Ship Cost - Shipbuilder Portion***

$$C_{F_{i1}} := F \cdot \frac{C_{L_{i1}}}{coul} \qquad C_{FM} := F \cdot C_{LM} \qquad C_{FM} = 13.62 \cdot Mdol$$

$$C_{F_{800}} := \frac{.104}{Mdol^{1.099}} \cdot \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{1.099} \qquad C_{F_{800}} \cdot coul = 27.38 \cdot Mdol$$

$$C_{F_{900}} := F \cdot \frac{C_{L_{900}}}{coul} \qquad C_{F_{900}} = 17.88$$

| $\frac{C_{F_{i1}} \cdot coul}{Mdol}$ |
|---|
| 11.31 |
| 36.47 |
| 24.84 |
| 12.5 |
| 41.97 |
| 7.1 |
| 1.99 |

**Total Follow Ship Construction Cost: (BCC)**

$$C_{FCC} := \sum_{i1} \frac{C_{F_{i1}} \cdot Mdol}{coul} + \frac{C_{F_{800}} \cdot coul}{Mdol} + C_{F_{900}} + \frac{C_{FM}}{Mdol} \qquad C_{FCC} \cdot coul = 195.07 \cdot Mdol$$

**+ Profit:**

$$F_P := .1 \qquad C_{FP} := F_P \cdot C_{FCC} \cdot coul \qquad C_{FP} = 19.51 \cdot Mdol \qquad \#$$

**= Follow Ship Price:**

$$P_F := C_{FCC} \cdot coul + C_{FP} \qquad P_F = 214.58 \cdot Mdol$$

**+ Change Orders:**

$$C_{FCORD} := .08 \cdot P_L \qquad C_{FCORD} = 23.58 \cdot Mdol \qquad \#$$

**= Total Follow Ship Shipbuilder Portion:**

$$C_{FSB} := P_F + C_{FCORD} \qquad C_{FSB} = 238.16 \cdot Mdol$$

## *b. Follow Ship Cost - Government Portion*

**Other support:** $C_{FOTH} := .025 \cdot P_F \qquad C_{FOTH} = 5.36 \cdot Mdol$ #

**+ Program Manager's Growth:** $C_{FPMG} := .05 \cdot P_F$ #

**number of helo's:** $N_{HELO} = 2$

**+ Ordnance and Electrical GFE:**
**(Military Payload GFE)**

$$C_{FMPG} := \left( .3 \cdot \frac{Mdol}{lton} \cdot W_{MP} + 18.710 \cdot Mdol \cdot N_{HELO} \right) \cdot F_I$$

$$C_{FMPG} = 400.98 \cdot Mdol$$

**+ HM&E GFE (boats, IC):** $C_{FHMEG} := .02 \cdot P_F$ $C_{FHMEG} = 4.29 \cdot Mdol$ #

**+ Outfittimg Cost:** $C_{FOUT} := .04 \cdot P_F$ $C_{FOUT} = 8.58 \cdot Mdol$ #

**= *Total Follow Ship Government Cost:***

$C_{FGOV} := C_{FOTH} + C_{FPMG} + C_{FMPG} + C_{FHMEG} + C_{FOUT}$ $C_{FGOV} = 429.95 \cdot Mdol$

## c. Total Follow Ship End Cost:
## (Must always be less than SCN appropriation)

*** *Total Follow Ship End Cost:***

$C_{FEND} := C_{FSB} + C_{FGOV}$ $C_{FEND} = 668.11 \cdot Mdol$

## d. Total Follow Ship Acquisition Cost:

**+ Post-Delivery Cost (PSA):** $C_{FPDEL} := .05 \cdot P_F$ $C_{FPDEL} = 10.73 \cdot Mdol$ #

**= *Total Follow Ship Acquisition Cost:*** $C_{FA} := C_{FEND} + C_{FPDEL}$ $C_{FA} = 678.83 \cdot Mdol$

## AVERAGE SHIP ACQUISITION COST:

$$C_{AV} := \frac{\frac{C_{FA} - C_{FMPG}}{F} \cdot \left(N_S - 1\right)^{\frac{\ln(2 \cdot R_L)}{\ln(2)}} + \left(N_S - 1\right) \cdot C_{FMPG} + C_{LA}}{N_S}$$ $C_{AV} = 668.68 \cdot Mdol$

## 6. Life Cycle Cost:

***a. Research and development***

**Ship design and development:**

$$C_{SDD} := 1.1 \cdot \left(.571 \cdot \frac{C_{FSB}}{F} + .072 \cdot C_{LMPG}\right)$$ $C_{SDD} = 192.48 \cdot Mdol$ #

**+ Ship test and evaluation**

$$C_{STE} := 1.2 \cdot \left(.499 \cdot \frac{C_{FSB}}{F} + .647 \cdot C_{LMPG}\right)$$ $C_{STE} = 478.66 \cdot Mdol$ #

= ***Total Ship R&D Cost:***

$$C_{RD} := C_{SDD} + C_{STE} \qquad C_{RD} = 671.14 \cdot \mathrm{Mdol}$$

***b) Investment (less base facilities, unrep, etc)***

**Ships:**

$$C_{SPE} := \frac{C_{FA}}{F} \cdot N_S^{\frac{\ln(2 \cdot R_L)}{\ln(2)}} \qquad C_{SPE} = 12.66 \cdot \mathrm{Bdol}$$

**average ship cost:** $C_{AVG} := \dfrac{C_{SPE}}{N_S}$ $\qquad C_{AVG} = 633.09 \cdot \mathrm{Mdol}$

**+ Support Equipment (shore-based)**

**ship:** $C_{SSE} := .15 \cdot C_{SPE} \qquad C_{SSE} = 1.9 \cdot \mathrm{Bdol}$ #

**+ Spares and repair parts (shore supply)**

**ship:** $C_{ISS} := .1 \cdot C_{SPE} \qquad C_{ISS} = 1.27 \cdot \mathrm{Bdol}$ #

**= <u>Total Investment Cost</u>:** $C_{INV} := C_{SPE} + C_{SSE} + C_{ISS}$

$$C_{INV} = 15.83 \cdot \mathrm{Bdol}$$

## *c) Operations and Support*

**Personnel (Pay and Allowances)**

$$C_{PAY} := F_I \cdot \left[ .026184 \cdot N_{C_1} + .01151 \cdot \left( N_{C_2} + N_{C_3} \right) \right] \cdot N_S \cdot L_S \cdot \mathrm{Mdol} \qquad C_{PAY} = 2.05 \cdot \mathrm{Bdol}$$

$$C_{TAD} := F_I \cdot \left( N_{C_1} + N_{C_2} + N_{C_3} \right) \cdot N_S \cdot L_S \cdot 2.6 \cdot 10^{-6} \cdot \mathrm{Mdol} \qquad C_{TAD} = 0.41 \cdot \mathrm{Mdol}$$

$$C_{PERS} := C_{PAY} + C_{TAD} \qquad C_{PERS} = 2.05 \cdot \mathrm{Bdol}$$

**+ Operations:** #

**Operating hours/year:** $H := 2500 \cdot \mathrm{hr}$

$$C_{OPS} := N_S \cdot L_S \cdot \left[ F_I \cdot \mathrm{Kdol} \cdot \left[ 188. + 2.232 \cdot \left( N_{C_1} + N_{C_2} + N_{C_3} \right) - \frac{H}{26.9 \cdot \mathrm{hr}} \right] + \frac{C_{AVG}}{769.2} + \frac{C_{FMPG}}{196} \right]$$

$$C_{OPS} = 2.17 \cdot \mathrm{Bdol}$$

+ **Maintenance**

$$C_{MTC} := N_S \cdot L_S \cdot \left[ F_I \cdot Kdol \cdot \left[ 2967 + 4.814 \cdot \left( N_{C_1} + N_{C_2} + N_{C_3} \right) - \frac{H}{3.05 \cdot hr} \right] + \frac{C_{AVG}}{156.25} \right]$$

$$C_{MTC} = 5.45 \circ Bdol$$

+ **Energy (Assumes all operation at Endurance Power with no electric load)**

**Fuel Rate:** $FR \cdot P_{eBAVG} = 4.8 \circ \frac{lton}{hr}$ $\qquad C_{FUEL} := .9 \cdot \frac{dol}{gal}$ #

$$C_{EGY} := N_S \cdot L_S \cdot C_{FUEL} \cdot \frac{H}{6.8 \cdot \frac{lb}{gal}} \cdot FR \cdot P_{eBAVG} \qquad C_{EGY} = 2.14 \circ Bdol$$

+ **Replenishment Spares**

$$C_{REP} := C_{ISS} \cdot \frac{L_S - 4}{4} \qquad C_{REP} = 8.23 \circ Bdol$$

+ **Major Support (COH, ROH):**

$$C_{MSP} := N_S \cdot L_S \cdot \left[ 698. + 5.988 \cdot \left( N_{C_1} + N_{C_2} + N_{C_3} \right) - \frac{H}{10.36 \cdot hr} \right] \cdot Kdol \cdot F_I + .0022 \cdot C_{AVG}$$

$$C_{MSP} = 1.43 \circ Bdol$$

= ***Total Operation and Support Cost:*** $C_{OAS} := C_{PERS} + C_{OPS} + C_{MTC} + C_{EGY} + C_{REP} + C_{MSP}$

$$C_{OAS} = 21.47 \circ Bdol$$

## d. Residual Value:

$$RES := .5 \cdot C_{SPE} \cdot \left( 1 - \frac{2}{L_S} \right)^{L_S} \qquad RES = 0.8 \circ Bdol$$

## e. Total Program

* ***Total Life Cycle Cost (Undiscounted):*** $C_{LIFE} := C_{RD} + C_{INV} + C_{OAS} - RES$

$$C_{LIFE} = 37.16 \circ Bdol$$

## 7. Discounted Life Cycle Cost:

**Discount Rate:** $R_D := 0.10$ #

***a. Discounted R&D:*** **Length of R&D Phase:** $L_{RD} := 13$ #

end: $E_{RD} := Y_{IOC} + 2 - Y_B$ $E_{RD} = 12$ **(normalized to base year)**

start: $B_{RD} := E_{RD} - L_{RD} + 1$ $B_{RD} = 0$

$$F_{DRD} := \frac{\displaystyle\sum_{y=B_{RD}}^{E_{RD}} \frac{1}{(1+R_D)^y}}{L_{RD}} \qquad F_{DRD} = 0.6$$

$C_{DRD} := F_{DRD} \cdot C_{RD}$ $C_{DRD} = 403.39 \cdot Mdol$

***b. Discounted Investment:***

start: $B_{INV} := E_{RD} + 1$

end: $E_{INV} := B_{INV} + \mathrm{ceil}\left(\left(\frac{N_S - 1}{R_P}\right)\right)$ $E_{INV} = 20$

$L_{INV} := E_{INV} - B_{INV} + 1$ $L_{INV} = 8$

$$F_{DINV} := \frac{\displaystyle\sum_{y=B_{INV}}^{E_{INV}} \frac{1}{(1+R_D)^y}}{L_{INV}} \qquad F_{DINV} = 0.21$$

$C_{DINV} := F_{DINV} \cdot C_{INV}$ $C_{DINV} = 3.36 \cdot Bdol$

***c. Discounted O&S:***

start: $B_{OAS} := E_{INV} + 1$ $B_{OAS} = 21$

end: $E_{OAS} := B_{OAS} + L_S - 1$ $E_{OAS} = 50$

$L_{OAS} := E_{OAS} - B_{OAS} + 1$ $L_{OAS} = 30$

$$F_{DOAS} := \frac{\displaystyle\sum_{y=B_{OAS}}^{E_{OAS}} \frac{1}{(1+R_D)^y}}{L_{OAS}} \qquad F_{DOAS} = 0.05$$

$$C_{DOAS} := F_{DOAS} \cdot C_{OAS} \quad C_{DOAS} = 1 \cdot Bdol$$

### *d. Discounted Residual Value:*

$$RES_D := RES \cdot \left(\frac{1}{1+R_D}\right)^{E_{OAS}+1} \qquad RES_D = 6.19 \cdot Mdol$$

### *e. Total Discounted Life Cycle Cost:*

$$C_{DLIFE} := C_{DRD} + C_{DINV} + C_{DOAS} - RES_D \qquad C_{DLIFE} = 4.76 \cdot Bdol$$

# Appendix D

# MIT XIII-A Functional Ship Synthesis Model (DD13A-X Modelled)

# MIT XIII-A FUNCTIONAL SHIP SYNTHESIS MODEL

$hp \equiv \frac{33000 \cdot ft \cdot lbf}{min}$ $\quad knt \equiv 1.69 \cdot \frac{ft}{sec}$ $\quad mile \equiv knt \cdot hr$ $\quad lton \equiv 2240 \cdot lb$ **SHIP NAME: DD13A-X**

**Seawater / Air properеties:**

$T_{SW} := 59$ $\quad \rho_{SW} := 1.9905 \cdot \frac{slug}{ft^3}$ $\quad \nu_{SW} := 1.2817 \cdot 10^{-5} \cdot \frac{ft^2}{sec}$ $\quad \rho_A := .0023817 \cdot \frac{slug}{ft^3}$

**Designer input / acceptance of default values required for each yellow highlighted item.**

**Constraints requiring satisfaction and important comments are highlighted green.**

**This model also requires design parameter (DP) selection utilizing, and accounted for by, an integrated Excel spreadsheet. This Excel component is highlighted below. While satisfying each functional requirement (FR) a when prompted, access the speadsheet for DP definition by "double clicking" on the Excel Worksheet icon. Th spreadsheet is an interactive portion of this model. Prior to exiting the Excel component, update (save) for modifications to be incorporated.**

**Initial input values for $D_0$, $D_{10}$, $D_{20}$, and MAST are given in the $FR_6$ section only to allow proper functioning of Excel component. These values do not necessarily satisfy $FR_6$ and the decomposed child FRs. Therefore, actua values for these DPs must be input and verified to satisfy $FR_6$.**

$$\begin{bmatrix} W_x \\ A_x \\ CUM \end{bmatrix} :=$$

Worksheet

$$\begin{bmatrix} D_{0e} & D_{10e} & D_{20e} & MASTe \end{bmatrix}$$

## Customer Attributes:

**Sustained Speed:** $V_S := 28 \cdot knt$

**Endurance Speed:** $V_e := 20 \cdot knt$

**Range:** $E := 7500 \cdot mile$

**Stores period:** $T_S := 45 \cdot day$

**Manning:** **Determine manning/automation distribution using the functional allocation process by evaluating lowest level FRs prior to satisfying design equations. Some parametrics based on manning numbers, as well as automated system characteristics, impose additional implications incorporate into this model.**

**Officers:** $N_O := 15$ **Enlisted:** **Chief Petty Officers:** $N_{CPO} := 20$

**Crewmembers:** $N_{CR} := 91$ $\quad N_E := N_{CPO} + N_{CR}$

$N_E = 111$

## DD13A-X

| FR | DP (PAYLOAD NAME) | WT KEY | WT | VCG DATUM | VCG FT AD | AREA KEY | HULL FT2 | DKHS FT2 | CRUISE KW | BATTLE KW | WT MOMENT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.1 | NAVIGATION SYSTEM | W420 | 7.29 | 51.00 | 14.00 | A1132 | 0.00 | 848.30 | 55.99 | 53.50 | 473.85 |
| FR2 | **Cumulative DP2** | **WP FR2** | 7.29 | | | | 0.00 | 848.30 | 55.99 | 53.50 | |
| 3 | ADVANCED TOMAHAWK WEAPON CONTROL SYSTEM | W482 | 5.60 | 39.00 | -7.80 | NONE | 0.00 | 0.00 | 13.27 | 13.27 | 174.72 |
| 3 | COMBAT DF | W495 | 8.26 | 39.00 | 21.00 | A1141 | 0.00 | 448.00 | 15.47 | 19.34 | 495.60 |
| 3 | ELECTRONIC TEST & CHECKOUT | W499 | 1.10 | 43.05 | 10.80 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 59.24 |
| 3 | SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO | WF21 | 4.10 | 39.00 | -6.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 135.30 |
| FR3.x | **Cumulative DP3.x** | **WP FR3.x** | 19.06 | | | | 0.00 | 448.00 | 28.74 | 32.61 | |
| 3.1.1 | SPS-67 SURFACE SEARCH RADAR | W451 | 1.81 | 51.00 | -10.00 | A1121 | 0.00 | 70.00 | 8.00 | 0.00 | 74.21 |
| FR3.1.1 | **Cumulative DP3.1.1** | **WP FR3.1.1** | 1.81 | | | | 0.00 | 70.00 | 8.00 | 0.00 | |
| 3.1.2 | SQS-53C 5M BOW SONAR DOME ELEX W/MINE AVOIDANCE | W463 | 57.70 | 0.00 | 9.30 | A1122 | 1,942.00 | 0.00 | 39.00 | 39.00 | 536.61 |
| 3.1.2 | SSQ-61 BATHYTHERMOGRAPH | W465 | 0.31 | 37.14 | -10.90 | A1122 | 85.50 | 0.00 | 0.00 | 0.00 | 8.13 |
| 3.1.2 | SQQ-28 SONOBUOY PROCESSING SYSTEM | W466 | 5.26 | 51.00 | -44.86 | NONE | 0.00 | 0.00 | 1.15 | 1.15 | 32.30 |
| 3.1.2 | BATHYTHERMOGRAPH PROBES | WF29 | 0.21 | 37.14 | -6.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 6.54 |
| FR3.1.2 | **Cumulative DP3.1.2** | **WP FR3.1.2** | 63.48 | | | | 2,027.50 | 0.00 | 40.15 | 40.15 | |
| 3.1.3 | SPS-49(V)5 2-D AIR SEARCH RADAR | W452 | 9.03 | 51.00 | -7.10 | A1121 | 0.00 | 553.00 | 15.30 | 48.40 | 396.42 |
| 3.1.3 | X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL | W456 | 4.11 | 0.00 | 113.00 | NONE | 0.00 | 0.00 | 220.16 | 220.16 | 464.43 |
| 3.1.3 | 2X HARPOON SSM QUAD CANNISTER LAUNCHERS | W721 | 4.10 | 39.00 | 1.17 | A1220 | 0.00 | 0.00 | 0.00 | 1.60 | 164.70 |
| 3.1.3 | MK41 VLS 64-CELL | W721 | 107.72 | 38.07 | 1.14 | A1220 | 128.00 | 0.00 | 69.65 | 69.65 | 4,223.70 |
| 3.1.3 | HARPOON MISSILES -- 8 RDS IN CANNISTERS | WF21 | 3.78 | 39.00 | 5.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 166.32 |
| 3.1.3 | MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS) | WF21 | 144.00 | 38.07 | 0.34 | A1220 | 1,420.00 | 720.00 | 0.00 | 0.00 | 5,531.04 |
| FR3.1.3 | **Cumulative DP3.1.3** | **WP FR3.1.3** | 272.74 | | | | 1,548.00 | 1,273.00 | 305.11 | 339.81 | |
| 3.1.4 | SLQ-32[V]3 ACTIVE ECM | W472 | 4.40 | 39.00 | 20.60 | NONE | 0.00 | 0.00 | 6.40 | 6.40 | 262.24 |
| FR3.1.4 | **Cumulative DP3.1.4** | **WP FR3.1.4** | 4.40 | | | | 0.00 | 0.00 | 6.40 | 6.40 | |
| 3.2.1 | MK XII AIMS IFF | W455 | 2.32 | 51.00 | -5.00 | NONE | 0.00 | 0.00 | 3.20 | 4.00 | 106.72 |
| FR3.2.1 | **Cumulative DP3.2.1** | **WP FR3.2.1** | 2.32 | | | | 0.00 | 0.00 | 3.20 | 4.00 | |
| 3.3 | VLS WEAPON CONTROL SYSTEM | W482 | 0.70 | 38.07 | 2.54 | A1220 | 56.00 | 310.00 | 13.62 | 19.69 | 28.43 |
| FR3.3 | **Cumulative DP3.3** | **WP FR3.3** | 0.70 | | | | 56.00 | 310.00 | 13.62 | 19.69 | |
| 3.3.2 | MK 86 5"/54 GFCS | W481 | 7.50 | 51.00 | -4.00 | A1212 | 0.00 | 168.00 | 6.00 | 15.40 | 352.50 |
| 3.3.2 | 1X MK45 5IN/54 GUN [ERGM) | W710 | 36.80 | 47.11 | -6.20 | A1210 | 270.00 | 0.00 | 36.18 | 37.88 | 1,505.34 |
| 3.3.2 | MK45 5IN ERGM AMMO - 600 RDS | WF21 | 35.10 | 47.11 | -28.40 | A1210 | 798.00 | 68.00 | 0.00 | 0.00 | 656.58 |
| FR3.3.2 | **Cumulative DP3.3.2** | **WP FR3.3.2** | 79.40 | | | | 1,068.00 | 236.00 | 42.18 | 53.28 | |
| 3.3.3 | ASW CONTROL SYSTEM [ASWCS] W/SSTD | W483 | 3.75 | 39.00 | -12.60 | A1240 | 320.00 | 0.00 | 8.61 | 8.61 | 99.00 |
| 3.3.3 | 2X MK32 SVTT ON DECK | W750 | 5.55 | 39.00 | 2.20 | A1244 | 0.00 | 368.00 | 2.00 | 5.00 | 228.66 |
| 3.3.3 | MK46 LWT ASW TORPEDOES -- 6 RDS IN SVTT TUBES | WF21 | 1.36 | 39.00 | 2.50 | A1240 | 368.00 | 0.00 | 0.00 | 0.00 | 56.44 |
| FR3.3.3 | **Cumulative DP3.3.3** | **WP FR3.3.3** | 10.66 | | | | 688.00 | 368.00 | 10.61 | 13.61 | |
| 3.3.4 | MK92 MFCS - STIR/CORT/IADT/CEC | W482 | 6.29 | 51.00 | -1.40 | NONE | 0.00 | 0.00 | 50.30 | 85.80 | 311.98 |
| FR3.3.4 | **Cumulative DP3.3.4** | **WP FR3.3.4** | 6.29 | | | | 0.00 | 0.00 | 50.30 | 85.80 | |
| 3.4 | CIC W/UYQ-44 & 2X LSD | W410 | 19.34 | 0.00 | 35.58 | A1131 | 1,953.00 | 448.00 | 45.03 | 45.03 | 688.12 |
| 3.4 | ADVANCED DIGITAL C4I (JTIDS/LINK 16/LINK22/TADIXS/TACINTEL) | W440 | 37.91 | 51.00 | -46.84 | A1110 | 1,230.60 | 1,270.40 | 35.76 | 39.67 | 157.71 |
| FR3.4 | **Cumulative DP3.4** | **WP FR3.4** | 57.25 | | | | 3,183.60 | 1,718.40 | 80.79 | 84.70 | |
| 3.5 | LAMPS MKIII 18 X MK46 TORP & SONOBUOYS & PYRO | WF22 | 9.87 | 38.07 | 4.80 | A1374 | 0.00 | 588.00 | 0.00 | 0.00 | 423.13 |
| 3.5 | LAMPS MKIII 2 X SH-60B HELOS AND HANGAR (BASED) | WF23 | 12.73 | 38.07 | 4.50 | A1340 | 0.00 | 3,406.00 | 5.60 | 5.60 | 541.92 |
| 3.5 | LAMPS MKIII AVIATION SUPPORT AND SPARES | WF26 | 9.42 | 38.07 | 5.00 | A1390 | 357.00 | 0.00 | 0.00 | 0.00 | 405.72 |
| 3.5 | LAMPS MKIII:AVIATION FUEL [JP-5] | WF42 | 63.80 | 0.00 | 10.40 | A1380 | 0.00 | 0.00 | 0.00 | 0.00 | 663.52 |
| 3.5 | LAMPS MKIII AVIATION FUEL SYS | W542 | 4.86 | 38.07 | -11.00 | A1380 | 30.00 | 0.00 | 2.00 | 2.90 | 131.56 |
| 3.5 | LAMPS MKIII RAST/RAST CONTROL/HELO CONTROL | W588 | 31.10 | 38.07 | -1.60 | A1312 | 219.00 | 33.00 | 4.40 | 4.40 | 1,134.22 |
| 3.5 | LAMPS MKIII AVIATION SHOP AND OFFICE | W665 | 1.04 | 38.07 | -4.50 | A1360 | 194.00 | 75.00 | 0.00 | 0.00 | 34.91 |
| FR3.5 | **Cumulative DP3.5** | **WP FR3.5** | 132.82 | | | | 800.00 | 4,102.00 | 12.00 | 12.90 | |
| FR3 | **Cumulative DP3** | **WP FR3** | 650.93 | | | | 9,371.10 | 8,525.40 | 601.10 | 692.95 | |
| 4.1 | SLQ-32[V]3 - MK36 DLS W/6 LAUNCHERS | W474 | 0.96 | 39.00 | 5.39 | NONE | 0.00 | 0.00 | 2.40 | 2.40 | 42.61 |
| FR4.1 | **Cumulative DP4.1** | **WP FR5.1** | 0.96 | | | | 0.00 | 0.00 | 2.40 | 2.40 | |
| 4.2.1 | AN/SLQ-25A NIXIE | W473 | 0.24 | 37.14 | -6.20 | A1142 | 200.00 | 0.00 | 3.00 | 4.20 | 7.43 |
| FR4.2.1 | **Cumulative DP4.2.1** | **WP FR4.3.1** | 0.24 | | | | 200.00 | 0.00 | 3.00 | 4.20 | |
| 4.2.4 | MK36 DLS SRBOC CANNISTERS - 100 RDS | WF21 | 2.20 | 39.00 | 11.60 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 111.32 |
| FR4.2.4 | **Cumulative DP4.2.4** | **WP FR4.3.4** | 2.20 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| FR4 | **Cumulative DP4** | **WP FR4** | 3.40 | | | | 200.00 | 0.00 | 5.40 | 6.60 | |
| 5.1 | SQS-53C 5M BOW SONAR DOME HULL DAMPING | W636 | 6.70 | 0.00 | -2.50 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | -16.75 |
| FR5.1 | **Cumulative DP5.1** | **WP FR5.1** | 6.70 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| 5.4.1 | 64-CELL VLS MAGAZINE DEWATERING SYSTEM | W529 | 7.00 | 38.07 | -0.46 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 263.27 |
| FR5.4.1 | **Cumulative DP5.5.1** | **WP FR5.5.1** | 7.00 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| FR5 | **Cumulative DP5** | **W FR5** | 13.70 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| 6.1.2 | STEEL LANDING PAD [ON HULL] - SH-60 CAPABLE | W111 | 10.70 | 37.14 | 0.20 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 399.54 |
| 6.1.2 | 64 CELL VLS ARMOR - LEVEL III HY-80 | W164 | 28.00 | 43.05 | -10.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 925.48 |
| 6.1.2 | MK45 GUN HY-80 ARMOR LEVEL II | W164 | 9.00 | 47.11 | -8.00 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | 351.95 |
| 6.1.2 | SQS-53C 5M BOW SONAR DOME W/MINE AVOIDANCE | W165 | 85.70 | 0.00 | -1.50 | NONE | 0.00 | 0.00 | 0.00 | 0.00 | -128.55 |
| FR6 | **Cumulative DP6** | **WP FR6** | 133.40 | | | | 0.00 | 0.00 | 0.00 | 0.00 | |
| | **GROUP WF20 (expendable ordnance)** | **WF20** | 222.77 | | | | 2,943.00 | 4,782.00 | | | |
| | **VARIABLE MILITARY PAYLOAD (WF20+WF42) (exp ord + helo fuel)** | **WVP** | 286.57 | | | | | | | | |
| | **ARMAMENT (WP500,WP600,W7,WF20)** | | | | | | 3,784.00 | 5,258.00 | | | |
| | | | | | | | | | KWP | | |
| | ***TOTAL PAYLOAD*** | **WP** | 808.72 | | | | 9,571.10 | 9,373.70 | 662.49 | 753.05 | 22,688.10 |

***DATUM DEFINITIONS:***

| | | | | | |
|---|---|---|---|---|---|
| **DEPTH0** | 50.58 | **WF20** | 222.77 | **WP** | 808.72 |
| **DEPTH3** | 47.11 | **WF23** | 12.73 | **WVP** | 286.57 |
| **DEPTH6.5** | 43.05 | **WF42** | 63.80 | **VCG P:** | 28.05 |
| **DEPTH10** | 39.00 | | | **VCG VP:** | 30.35 |
| **DEPTH15** | 38.07 | **W164** | 37.00 | **KWP** | 662.49 |
| **DEPTH20** | 37.14 | **W165** | 85.70 | | |
| **BL** | 0.00 | **WP400** | 176.59 | **A HPC** | 5,787.10 |
| **MAST BASE** | 51.00 | **WP500** | 42.96 | **A DPC** | 4,115.70 |
| | | **WP600** | 7.74 | **A HPA** | 3,784.00 |
| | | **W7** | 154.17 | **A DPA** | 5,258.00 |

**Total Manning:** $N_T := N_E + N_O$ $N_T = 126$

## $FR_1$ = <u>Move through water</u>

## $DP_1$ = <u>Propulsion system</u>

## Decomposition:

**Upper level FR and DP definitions given below**

**$FR_{1.1}$ = Produce propulsive power to achieve sustained speed**

**$DP_{1.1}$ = Main propulsion engines (MPE's)**

**Number and brake horsepower of propulsion engines:**

$N_{PENG} := 4$ $P_{BPENG} := 22750 \cdot hp$ **Propulsion Engines (PE) - GE LM2500-21's Contained in standard modules**

$L_{mod} := 26 \cdot ft$ $B_{mod} := 9 \cdot ft$ $H_{mod} := 10 \cdot ft$

$P_{IBRAKE} := N_{PENG} \cdot P_{BPENG}$ $P_{IBRAKE} = 91000 \circ hp$

$\eta := 0.97$ $P_I := \eta \cdot P_{IBRAKE}$ $P_I = 88270 \circ hp$

**$FR_{1.1.4}$ = Provide air to support engine combustion**

**$DP_{1.1.4}$ = Engine inlet ducting**

**$FR_{1.1.5}$ = Remove combustion products**

**$DP_{1.1.5}$ = Engine exhaust ducting**

**Inlet/exhaust Xsect area for PE:** $A_{IE} := 135.2 \cdot ft^2$ $A_{PIE} := N_{PENG} \cdot A_{IE}$ $A_{PIE} = 540.8 \circ ft^2$

**Deckhouse decks impacted by propulsion and generator inlet/exhaust:** $N_{DIE} := 2$

**Engine Inlet/Exhaust (Deckhouse) :** $A_{DIEP} := 1.4 \cdot N_{DIE} \cdot A_{PIE}$ $A_{DIEP} = 1514.24 \circ ft^2$

**Hull decks impacted by propulsion inlet/exhaust:** $N_{HPIE} := 0$

**Engine Inlet/Exhaust (Hull):** $A_{HIEP} := 1.4 \cdot N_{HPIE} \cdot A_{PIE}$ $A_{HIEP} = 0 \circ ft^2$

**$FR_{1.2}$ = Provide propulsive power at usable speed (rpm)** **$DP_{1.2}$ = Reduction gear**

**$FR_{1.2.2}$ = Cool reduction gear** **$DP_{1.2.2}$ = Lube oil system**

**LO weight:** $W_{F46} := 7.2 \cdot lton$ $\gamma_{LO} := 39 \cdot \frac{ft^3}{lton}$

**Allow for tank structure and expansion:** $V_{LO} := 1.02 \cdot 1.05 \cdot W_{F46} \cdot \gamma_{LO}$ $V_{LO} = 300.74 \, ft^3$

**$FR_{1.3}$ = Transfer power to water** **$DP_{1.3}$ = CRP propeller**

**Number of propellers:** $N_P := 0.50 \cdot N_{PENG}$ $N_P = 2$

**Select propeller diameter:** $D_P := 19 \cdot ft$

**Props:**
**(245)**

$$W_{PR} := 1.15 \cdot \left[ .05575 \cdot lb \cdot \left( \frac{D_P}{ft} \right)^{5.497 - \frac{0.0433}{ft} \cdot D_P} \cdot N_P \right]$$ $W_{PR} = 54.33 \, lton$

**$FR_{1.3.1}$ = Receive speed (rpm) input from reduction gear** **$DP_{1.3.1}$ = Shaft**

**Select shaft length:** $L_S := 100 \cdot ft$ $N_S := N_P$

**Shafting:**
**(243)**

$$W_S := 1.15 \cdot \left( .356 \cdot \frac{lton}{ft} \cdot N_S \cdot L_S \right)$$ $W_S = 81.88 \, lton$

**Total Shafting and Propellers:** $W_{ST} := W_S + W_{PR}$ $W_{ST} = 136.21 \, lton$

**$FR_{1.4}$ = Control speed and direction of movement locally** **$DP_{1.4}$ = Engineering operations station (EOS)**

**Combined automated systems:** $W_{AUTO} := 1.0 \cdot lton$ $kW_{AUTO} := 5.0 \cdot kW$ $A_{AUTO} := 50.0 \cdot ft^2$

$FR_{1.5}$ = **Control speed and direction of movement remotely** $DP_{1.5}$ = **Lee helm**

**Cumulative effects of above design decisions:**

**Propulsion:** $kW_P := .00466 \cdot \frac{kW}{hp} \cdot P_{IBRAKE} + kW_{AUTO}$ $kW_P = 429.06 \cdot kW$

**Machinery Box (assumed near midships)**

$B_{MB} := 1.5 \cdot B_{mod} \cdot N_{PENG}$ $L_{MB} := 1.5 \cdot L_{mod} \cdot N_S$ $H_{MB} := 2.5 \cdot H_{mod}$

$B_{MB} = 54 \cdot ft$ $L_{MB} = 78 \cdot ft$ $H_{MB} = 25 \cdot ft$

**Machinery Box Area:** $A_{MB} := L_{MB} \cdot B_{MB}$ $A_{MB} = 4212 \cdot ft^2$

*** Note: All automated systems contained within Machinery Box area and volume**

**Machinery Box Volume:** $V_{MB} := H_{MB} \cdot A_{MB}$ $V_{MB} = 105300 \cdot ft^3$

**Propulsion (200)**

**Basic Machinery:**
**(230+241/242+250-290)** $W_{BM} := P_I \cdot \frac{lb}{hp} \cdot \left[ 9.0 + 12.4 \cdot \left( P_I \cdot \frac{10^{-5}}{hp} - 1 \right)^2 \right]$ $W_{BM} = 361.38 \cdot lton$

## $FR_2$ = <u>Maintain desired course</u> $DP_2$ = <u>Maneuvering and control system</u>

## Decomposition:

**Upper level FR and DP definitions given below**

$FR_{2.1}$ = **Determine if course is "safe"** $DP_{2.1}$ = **Navigation equipment**

*** Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with selected navigation system ($DP_{2.1}$) in Payload Spreadsheet**
**Note 1: VCG Datum and VCG normally do not require modification**
**Note 2: These parameters are utilized further at the appropriate stage of design definition**

**Input Bridge and Chartroom area:** $A_{DB} := 570 \cdot ft^2$

**Gyro/IC/Navigation (420, 430):** $W_{IC} := 43.8 \cdot lton$

**$FR_{2.2}$ = Alter existing course** **$DP_{2.2}$ = Rudder**

**Steering:** $kW_S := 78.7 \cdot kW$

**$FR_{2.3}$ = Maneuver alongside pier** **$DP_{2.3}$ = Bow thrusters / APU's**

**Aux Propulsion (APU):** $W_{237} := 0 \cdot lton$ $VCG_{237} := 0 \cdot ft$

**Fin Stabilizers: (for one pair, electric power requirement = 50 kW)** $kW_{fins} := 0 \cdot kW$

**Total Propulsion:** $W_2 := W_{BM} + W_{ST} + W_{237} + W_{AUTO}$ **(Cumulative $FR_1$ and $FR_{2.3}$)**

$W_2 = 498.58 \circ lton$

## $FR_3$ = <u>Neutralize enemy targets</u> $DP_3$ = <u>Combat systems configuration</u>

## Decomposition:

**Upper level FR and DP definitions given below**

*** Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with all selected $DP_3$ and $DP_{3.X.X}$ systems in Payload Spreadsheet**
**Pertinent decomposition structure given in spreadsheet**
**Note 1: VCG Datum and VCG normally do not require modification**
**Note 2: These parameters are utilized further at the appropriate stage of design definition**

**$FR_{3.1}$ =Detect Targets** **$DP_{3.1}$ = Ship's sensors**

**$FR_{3.1.2}$ = Detect subsurface targets** **$DP_{3.1.2}$ = Sonar**

$C_{SD} := 0.28$ **SQS-53C Sonar:** $A_{SD} := 215 \cdot ft^2$ **(SQS-56: 27ft²; SQS-53C: 215ft²)**

**water:** $W_{498} := 87.9 \cdot lton$ $VCG_{498} := -1.2 \cdot ft$

**$FR_{3.2}$ = Classify targets** | **$DP_{3.2}$ = Surveillance systems with identification protocols**

**$FR_{3.3}$ = Engage targets** | **$DP_{3.3}$ = Weapons systems**

**$FR_{3.4}$ = Operate as "node" sharing information** | **$DP_{3.4}$ = Combat systems networking protocol**

**$FR_{3.5}$ = Provide target prosecution flexibility** | **$DP_{3.5}$ = Embarked helicopter**

$N_{HELO} := 2$ **(Use for $FR_{3.5}$ spreadsheet input)**

**Helo's:** **(Spreadsheet Output)** $W_{F23} := W_{x_2} \cdot lton$ $W_{F23} = 12.73 \cdot lton$ **($FR_{3.5}$)**

**Helo Fuel:** **(Spreadsheet Output)** $W_{F42} := W_{x_3} \cdot lton$ $W_{F42} = 63.8 \cdot lton$ **($FR_{3.5}$)**

**Allow for tank structure and expansion:** $\gamma_{HF} := 43 \cdot \frac{ft^3}{lton}$ $V_{HF} := 1.02 \cdot 1.05 \cdot W_{F42} \cdot \gamma_{HF}$

$V_{HF} = 2938.18 \cdot ft^3$

**Cumulative effects of above design decisions:**

**Payload Deck Area:** **(Spreadsheet Output)**

**Deckhouse:** **Armament (W500, W600, W700, WF20):** $A_{DPA} := A_{x_4} \cdot ft^2$ $A_{DPA} = 5258 \cdot ft^2$ **(cumulative $FR_3$)**

**Armament (all $W_{700}$):** **(Spreadsheet Output)** $W_7 := W_{x_{10}} \cdot lton$ $W_7 = 154.17 \cdot lton$ **(cumulative $FR_3$)**

## $FR_4$ = <u>Protect from enemy attack</u> | $DP_4$ = <u>Countermeasures methods</u>

## Decomposition:

**Upper level FR and DP definitions given below**

*** Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with selected $DP_{4.1}$ and $DP_{4.2.X}$ systems in Payload Spreadsheet**
**Note 1: VCG Datum and VCG normally do not require modification**
**Note 2: These parameters are utilized further at the appropriate stage of design definition**

**$FR_{4.1}$ = Neutralize enemy weapon's effect by "hard kill"** | **$DP_{4.1}$ = Self defense weapons**

**$FR_{4.2}$ = Neutralize enemy weapon's effect by "soft kill"** **$DP_{4.2}$ = Self defense decoys**

**$FR_{4.2.1}$ = Neutralize acoustic targeted weapons** **$DP_{4.2.1}$ = Deployable noisemakers (Nixie)**

**Command and Surveillance Payload:** $W_{P400} := W_{x_7} \cdot lton$ **(cumulative $FR_3$, $FR_{4.1}$, and $FR_{4.2.1}$)**
**($W_{400}$ less 420 and 430)**
**(Spreadsheet Output)** $W_{P400} = 176.59 \cdot lton$

**Payload Deck Areas: (Spreadsheet Outputs)**

**Hull:** **C&D (W400):** $A_{HPC} := A_{x_1} \cdot ft^2$ **(cumulative $FR_{2.1}$, $FR_3$, $FR_{4.1}$, and $FR_{4.2.1}$)**

$A_{HPC} = 5787.1 \cdot ft^2$

**Deckhouse:** **C&D (W400):** $A_{DPC} := A_{x_2} \cdot ft^2$ **(cumulative $FR_{2.1}$, $FR_3$, $FR_{4.1}$, and $FR_{4.2.1}$)**

$A_{DPC} = 4115.7 \cdot ft^2$

**Deckhouse payload area:** $A_{DPR} := 1.15 \cdot A_{DPA} + 1.23 \cdot A_{DPC}$ $A_{DPR} = 11109.01 \cdot ft^2$
**(including access)**

**$FR_{4.2.4}$ = Neutralize home on target weapons** **$DP_{4.2.4}$ = Deployable false targets (Chaf)**

**Ordnance:** $W_{F20} := W_{x_1} \cdot lton$ $W_{F20} = 222.77 \cdot lton$ **(cumulative $FR_3$ and $FR_{4.2.4}$)**
**(incl helo wt, WF23)**
**(Spreadsheet Output)**

**Variable Payload:** $W_{VP} := CUM_2 \cdot lton$ $W_{VP} = 286.57 \cdot lton$ **(cumulative $FR_3$ and $FR_{4.2.4}$)**
**(Spreadsheet Output)**

**$FR_{4.3}$ = Reduce liklihood of enemy detection** **$DP_{4.3}$ = Signatures reduction**

**$FR_{4.3.2}$ = Reduce detection by EM sensing methods** **$DP_{4.3.2}$ = Exploitation of EM pulse characteristics**

**$FR_{4.3.2.1}$ = Minimize radar cross section (RCS)** **$DP_{4.3.2.1}$ = Superstructure construction**

**Living Deck Area:** $A_{COXO} := 225 \cdot ft^2$ $A_{DO} := 75 \cdot N_O \cdot ft^2$ $A_{DO} = 1125 \cdot ft^2$
**(Deckhouse)**

$$A_{DL} := A_{COXO} + A_{DO} \qquad A_{DL} = 1350 \cdot ft^2$$

**Maintenance:** $$A_{DM} := .05 \cdot (A_{DPR} + A_{DL}) \qquad A_{DM} = 622.95 \cdot ft^2$$

**Assume inlet/exhaust Xsect area for PE is much greater than inlet/exhaust Xsect area for GE and deckhouse decks impacted by propulsion inlet/exhaust and generator inlet/exhaust are equal:**

$$A_{DIEP} = 1514.24 \cdot ft^2 \qquad A_{DIE} := 1.20 \cdot A_{DIEP} \qquad A_{DIE} = 1817.09 \cdot ft^2$$

**Total Required Deckhouse Area and Volume:**

**Average deckhouse deck height:** $H_{DKd} := 9 \cdot ft$ $\qquad H_{DK} := H_{DKd}$

$$A_{DR} := A_{DPR} + A_{DL} + A_{DM} + A_{DB} + A_{DIE} \qquad A_{DR} = 15469.05 \cdot ft^2$$

$$V_{DR} := H_{DKd} \cdot A_{DR} \qquad V_{DR} = 139221.45 \cdot ft^3$$

**Size Deck House:** Must satisfy $C_{8.1}$: Available deckhouse volume $\geq$ Required deckhouse volume

and $C_{9.1}$: Available arrangeable deckhouse area $\geq$ Required arrangeable deckhouse area

*** Set deckhouse volume ($V_D$) > or = to $V_{DR}$. Therefore $A_{DA}$ also > or = to $A_{DR}$

$$V_D := 156000 \, ft^3 \qquad V_D = 156000 \cdot ft^3$$

$$A_{DA} := \frac{V_D}{H_{DKd}} \qquad A_{DA} = 17333.33 \cdot ft^2 \qquad A_{DR} = 15469.05 \cdot ft^2$$

$C_{DHMAT} := 2$ **(Deckhouse Material: Aluminum - $C_{DHMAT} = 1$; Steel - $C_{DHMAT} = 2$)**

$$\rho_{DH} := \text{if}(C_{DHMAT} = 1, 0.0007, 0.001429)$$

**Deckhouse (150):** $$W_{DH} := \rho_{DH} \cdot \frac{lton}{ft^3} \cdot V_D \qquad W_{DH} = 222.92 \cdot lton$$

## $FR_5$ = Conduct sustained underway operations    $DP_5$ = Support / Auxiliary systems

## Decomposition:

**Upper level FR and DP definitions given below**

*** Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with all selected $DP_{5.1}$ and $DP_{5.4.1}$ systems in Payload Spreadsheet**
**Note 1: VCG Datum and VCG normally do not require modification**
**Note 2: These parameters are utilized further at the appropriate stage of design definition**

**$FR_{5.1}$ = Ensure habitable conditions**    **$DP_{5.1}$ = Crew support / habitability features**

**$FR_{5.1.1}$ = Supply stores (food) sufficient to feed the crew for stores period**    **$DP_{5.1.1}$ = Provisions loadout**

**Unrep and handling:** $kW_{RH} := 5.0 \cdot kW$

**Hull Stores** $A_{HS} := 300 \cdot ft^2 + .0158 \cdot \frac{ft^2}{lb} \cdot N_T \cdot 9 \cdot \frac{lb}{day} \cdot T_S$    $A_{HS} = 1106.27 \circ ft^2$

**Provisions:** $W_{F31} := N_T \cdot 9 \cdot \frac{lb}{day} \cdot T_S$    $W_{F31} = 22.78 \circ lton$

**General stores:** $W_{F32} := .0009598 \cdot \frac{lton}{day} \cdot T_S \cdot N_T$    $W_{F32} = 5.44 \circ lton$

**$FR_{5.1.2}$ = Supply fresh water**    **$DP_{5.1.2}$ = Potable water system**

**Potable Water:**

**Water weight:** $W_{F52} := N_T \cdot .15 \cdot lton$    $W_{F52} = 18.9 \circ lton$

**Allow for tank structure:** $\gamma_W := 36 \cdot \frac{ft^3}{lton}$

$V_W := 1.02 \cdot W_{F52} \cdot \gamma_W$    $V_W = 694.01 \circ ft^3$

**distiller:** $Q_{DS} := 6.5 \cdot N_T + 250$

$FR_{5.1.3}$ **= Control climate for crew comfort and machinery operations**

$DP_{5.1.3}$ **= Climate control system**

**Heating:** $kW_H := .0013 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot \left[H_{DK} \cdot \left(4.0 \cdot A_{DR}\right)\right]$ $kW_H = 904.94 \circ kW$

**Ventilation:** $kW_{CPS} := .00026 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot \left[H_{DK} \cdot \left(4.0 \cdot A_{DR}\right)\right]$ $kW_{CPS} = 260.62 \circ kW$

**(zero if no CPS)**

$kW_V := .19 \cdot \left(kW_H + kW_P\right) + kW_{CPS}$ $kW_V = 514.08 \circ kW$

**Air Conditioning:** $kW_{AC} := .67 \cdot \left[ .1 \cdot kW \cdot N_T + \left(.0015 \cdot \frac{kW}{ft^3}\right) \cdot 1.3 \cdot \left[0.47 \cdot H_{DK} \cdot \left(4.0 \cdot A_{DR}\right)\right] + .1 \cdot kW_P \right]$

$kW_{AC} = 379.15 \circ kW$

**Aux Boiler and FW:** $kW_B := .94 \cdot N_T \cdot kW$ $kW_B = 118.44 \circ kW$
**(electric boiler)**

**aux steam (electric aux boiler): hotel steam:**

$Q_{HS} := 15 \cdot N_T$ $W_{517} := .0013 \cdot \left(Q_{HS} + Q_{DS}\right) \cdot lton$ $W_{517} = 3.85 \circ lton$

**CPS:** **($W_{CPS}$=30lton, CPS not installed = 0 lton)** $W_{CPS} := 30 \cdot lton$

**environmental support:** $W_{593} := 10 \cdot lton$

$FR_{5.1.4}$ **= Provide for crew hygiene**

$DP_{5.1.4}$ **= Plumbing system**

**Sewage:** $V_{SEW} := N_T \cdot 2 \cdot ft^3$ $V_{SEW} = 252 \circ ft^3$

$FR_{5.1.5}$ **= Support feeding of crew**

$DP_{5.1.5}$ **= Food service equipment**

$FR_{5.1.6}$ **= Illuminate spaces**

$DP_{5.1.6}$ **= Lighting system**

**Lighting:** $kW_L := .0002053 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot \left[H_{DK} \cdot \left(4.0 \cdot A_{DR}\right)\right]$ $kW_L = 205.79 \circ kW$

$FR_{5.1.7}$ = **Allow crew escape when necessary** $DP_{5.1.7}$ = **Life boats**

**Mission outfit:** $W_{P600} := W_{x_9} \cdot lton$ $W_{P600} = 7.74 \cdot lton$ **($FR_{3.5}$ and $FR_{5.1}$)**
**(Spreadsheet Output)**

$FR_{5.2}$ = **Maintain equipment in operating condition** $DP_{5.2}$ = **Maintenance philosophy**

**Services and Work Spaces:** $kW_{SERV} := .35 \cdot N_T \cdot kW$ $kW_{SERV} = 44.1 \cdot kW$

$FR_{5.3}$ = **Communicate information** $DP_{5.3}$ = **Communications equipment**

**Masts:** $W_{171} := 2.0 \cdot lton$

$FR_{5.4}$ = **Combat damage** $DP_{5.4}$ = **Damage control (DC) systems**

**Mission handling/support:** $W_{P500} := W_{x_8} \cdot lton$ $W_{P500} = 42.96 \cdot lton$ **(cumulative $FR_5$)**
**(Spreadsheet Output)**

**Payload Deck Area:** **(Spreadsheet Output)**

**Hull:** **Armament (W500, W600, W700, WF20):** $A_{HPA} := A_{x_3} \cdot ft^2$ $A_{HPA} = 3784 \cdot ft^2$ **(cumulative $FR_3$ - $FR_5$)**

**Hull payload area:** $A_{HPR} := 1.15 \cdot A_{HPA} + 1.23 \cdot A_{HPC}$ $A_{HPR} = 11469.73 \cdot ft$
**(including access)**

**Payload Cruise Electric Power Requirement:** $kW_{PAY} := CUM_5 \cdot kW$
**(Spreadsheet Output)**

$kW_{PAY} = 662.49 \cdot kW$ **(cumulative $FR_2$ - $FR_5$)**

**Firemain:** $kW_F := .0001 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot \left[H_{DK} \cdot (4.0 \cdot A_{DR})\right]$ $kW_F = 100.24 \cdot kW$

**Waste Oil:** $V_{WASTE} := 1400 \cdot ft^3$

$FR_{5.5}$ = **Secure position while underway** $DP_{5.5}$ = **Anchoring system**

**$FR_{5.6}$ = Secure position while in port** **$DP_{5.6}$ = Mooring system**

**Note: Following equations primarily account for cumulative effects / Listed here since $FR_{5.6}$ is last FR prior to designing electrical system ($DP_{5.7}$)**

$V_{AUX} := 1.2 \cdot V_{MB}$ $\quad V_{AUX} = 126360 \cdot ft^3$

**aux sys operating fluids:** $W_{598} := 60.5 \cdot lton$

$X := H_{DK} \cdot (6.0 \cdot A_{DR})$ $\quad X = 835328.68 \cdot ft^3$ **(X approximates $V_T$)**

$$W_{AUX} := \left[ .000772 \cdot \left(\frac{X}{ft^3}\right)^{1.443} + 5.14 \cdot \frac{X}{ft^3} + 6.19 \cdot \left(\frac{X}{ft^3}\right)^{.7224} + 377 \cdot N_T + 2.74 \cdot \frac{P_I}{hp} \right] \cdot 10^{-4} \cdot lton + 113.8 \cdot lton$$

$W_{AUX} = 610.93 \cdot lton$

**environmental support:** $W_5 := W_{AUX} + W_{P500} + W_{517} + W_{593} + W_{598} + W_{CPS}$ $\quad W_5 = 758.23 \cdot lton$

**Aux Machinery:** $kW_A := .22 \cdot N_T \cdot kW + kW_{fins}$ $\quad kW_A = 27.72 \cdot kW$

**Miscellaneous:** $kW_M := 46.1 \cdot kW$

**Non-Payload Functional Load:**

$$kW_{NP} := kW_P + kW_S + kW_L + kW_M + kW_H + kW_V + kW_{AC} + kW_B + kW_F + kW_{RH} + kW_A + kW_{SER}$$

**Maximum Functional Load:**

$kW_{MFL} := kW_{PAY} + kW_{NP}$ $\quad kW_{MFL} = 3515.81 \cdot kW$

**MFL with margins:**
**Required to satisfy $C_{10}$ = Incorporate design growth margins**

$kW_{MFLM} := 1.2 \cdot 1.2 \cdot kW_{MFL}$ $\quad kW_{MFLM} = 5062.77 \cdot kW$

**24 hour electrical load:**

$$kW_{24} := .5\cdot(kW_{MFL} - kW_P - kW_S) + .8\cdot(kW_P + kW_S) \qquad kW_{24} = 1910.23 \circ kW$$

**with margin (design):** $kW_{24AVG} := 1.2\cdot kW_{24}$ $\qquad kW_{24AVG} = 2292.28 \circ kW$

**$FR_{5.7}$ = Provide electrical power** **$DP_{5.7}$ = Electrical system**

**$FR_{5.7.1}$ = Generate electrical power** **$DP_{5.7.1}$ = Ship's service generators**

**Ship Service Generators:** $N_G := 3$ $\quad kW_G := 3000\cdot kW$ **Generator Engines (GE) - DDA 501-k34's**

**Installed Electrical Power required per generator:**

$$kW_{GREQ} := \frac{kW_{MFLM}}{(N_G - 1)\cdot 0.9} \qquad kW_{GREQ} = 2812.65 \circ kW$$

$$kW_G = 3000 \circ kW$$

**Selection of generator type and quantity must satisfy $C_7$:**
**Installed electrical power > Required electrical power**

$$ERR_{KW} := \frac{kW_G - kW_{GREQ}}{kW_{GREQ}}$$

$$ERR_{KW} = 0.067$$

**Electrical Plant (300)** $W_3 := 50\cdot lton + .03214\cdot\frac{lton}{kW}\cdot N_G\cdot kW_G$ $\qquad W_3 = 339.26 \circ lton$

**$FR_{5.7.1.1}$ = Provide prime mover to turn rotor** **$DP_{5.7.1.1}$ = Generator engine**

**$FR_{5.7.1.1.2}$ = Provide fuel for continuous engine operation** **$DP_{5.7.1.1.2}$ = GE fuel system**

**Specific fuel rate for generator engines:** $FR_G := 0.288\cdot\frac{kg}{kW\cdot hr}$ $\qquad FR_G = 0.473 \circ \frac{lb}{hp\cdot hr}$

**Estimate Electric Fuel Rate:**

**Margin for instrumentation and machinery differences, $f(P_e/P_I)$:** $f_{1e} := 1.04$

**Specified fuel rate:** $FR_{GSP} := f_{1e} \cdot FR_G$

**Average fuel rate allowing for plant deterioration:** $FR_{GAVG} := 1.05 \cdot FR_{GSP}$

$$FR_{GAVG} = 0.69 \circ \frac{lb}{kW \cdot hr} \qquad FR_{GAVG} = 0.52 \circ \frac{lb}{hp \cdot hr}$$

**$FR_{5.7.1.1.4}$ = Provide air to support engine combustion** **$DP_{5.7.1.1.4}$ = Engine inlet ducting**

**$FR_{5.7.1.1.5}$ = Remove combustion products** **$DP_{5.7.1.1.5}$ = Engine exhaust ducting**

**Inlet/exhaust X-sect area for gen:** $A_{GIE} := 38.4\ ft^2$ $A_{eIE} := N_G \cdot A_{GIE}$

$A_{eIE} = 115.2 \circ ft^2$

**Deckhouse decks impacted by propulsion and generator inlet/exhaust:** $N_{DIE} = 2$

**Engine Inlet/Exhaust (Deckhouse):** $A_{DIEe} := 1.4 \cdot N_{DIE} \cdot A_{eIE}$

$A_{DIEe} = 322.56 \bullet ft^2$

**Hull decks impacted by generator inlet/exhaust:** $N_{HeIE} := 1$

**Engine Inlet/Exhaust (Hull):** $A_{HIEe} := 1.4 \cdot N_{HeIE} \cdot A_{eIE}$ $A_{HIEe} = 161.28 \bullet ft^2$

**$FR_{5.7.2}$ = Generate electrical power in emergency situation** **$DP_{5.7.2}$ = Emergency diesel generator**

**$FR_{5.7.3}$ = Distribute electrical power** **$DP_{5.7.3}$ = Electrical switchboards**

**$FR_{5.7.4}$ = Transport electrical power to equipment** **$DP_{5.7.4}$ = Cabling**

$W_{CC} := .04 \cdot (W_{P400} + W_{IC})$ $W_{CC} = 8.82 \circ lton$

$W_4 := W_{P400} + W_{IC} + W_{CC} + W_{498}$ $W_4 = 317.11 \circ lton$

**$FR_{5.7.5}$ = Isolate equipment locally** **$DP_{5.7.5}$ = Circuit breakers**

$FR_{5.8}$ = Provide fuel source

$DP_{5.8}$ = Fuel system

**Burnable propulsion endurance fuel weight:** **Must satisfy $C_{12}$ = Carry adequate fuel to transit endurance range (E) at endurance speed ($V_e$) - Compliance verified after satisfying $FR_6$**

$$W_{BP} := 1980 \cdot lton$$

**Tailpipe allowance and propulsion endurance fuel:** $TPA := .95$ **(shallow tanks)**

$$W_{FP} := \frac{W_{BP}}{TPA} \qquad W_{FP} = 2084.21 \cdot lton$$

**Allow for expansion and tank structure in required propulsion tank volume:** $\gamma_F := 43 \cdot \frac{ft^3}{lton}$

$$V_{FP} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{FP} \qquad V_{FP} = 95984.15 \cdot ft^3$$

**Burnable electrical endurance fuel weight:**

$$W_{Be} := \frac{E}{V_e} \cdot \left(kW_{24AVG} \cdot FR_{GAVG}\right) \qquad W_{Be} = 266.07 \cdot lton$$

**Tailpipe allowance and electrical endurance fuel:**

$$W_{Fe} := \frac{W_{Be}}{TPA} \qquad W_{Fe} = 280.08 \cdot lton$$

**Allow for expansion and tank structure in required electrical fuel tank volume:**

$$V_{Fe} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{Fe} \qquad V_{Fe} = 12898.36 \cdot ft^3$$

**Total ship fuel: (DFM)**

$$W_{F41} := W_{FP} + W_{Fe} \qquad W_{F41} = 2364.29 \cdot lton$$

$$V_F := V_{FP} + V_{Fe} \qquad V_F = 108882.51 \cdot ft^3$$

## $FR_6$ = <u>Operate on surface of water</u> $DP_6$ = <u>Hull form</u>

## Decomposition:

**Upper level FR and DP definitions given below**

**$FR_{6.1}$ = Enclose personnel and equipment** **$DP_{6.1}$ = Hull**

**$FR_{6.1.1}$ = Allow linear placement of equipment** **$DP_{6.1.1}$ = Hull extents**

**$FR_{6.1.1.1}$ = Facilitate longitudinal placement** **$DP_{6.1.1.1}$ = Length on design waterline**

**Input desired value:** $LWL := 501 \cdot ft$

**$FR_{6.1.1.2}$ = Facilitate transverse placement** **$DP_{6.1.1.2}$ = Beam**

Input desired value (use beam at DWL):
Must satisfy $C_{13}$ = Contain machinery box beam $B := 54 \cdot ft$ > or = $B_{MB} = 54 \cdot ft$

**Calculate Length to Beam Ratio and compare to historical monohull design trends given in Tables 1 - 4:** $C_{LB} := \frac{LWL}{B}$ $C_{LB} = 9.278$ **(7.5-10)**

**$FR_{6.1.2}$ = Allow verticle clearance for personnel and equipment** **$DP_{6.1.2}$ = Number of decks and average deck height**

**Number of hull decks:** $N_{decks} := 4$

**Average hull deck height:** $H_{DKh} := H_{DK}$ $H_{DKh} = 9 \cdot ft$

**$FR_{6.1.3}$ = Ensure watertight integrity** **$DP_{6.1.3}$ = Hull structure**

* Input parameters (W, $A_{hull}$, $A_{dkhs}$, kW) associated with all selected $DP_{6.1.3}$ systems in Payload Spreadsheet
Note 1: VCG Datum and VCG normally do not require modification
Note 2: These parameters are utilized further at the appropriate stage of design definition

**$FR_{6.1.3.2}$ = Prevent water from entering over the sides** **$DP_{6.1.3.2}$ = Depth at Station 10 ($D_{10}$)**

**Must satisfy the following constraints simultaneously:**

**$C_{14}$ = Contain machinery box height**

**$C_{15}$ = $D_{10}$ must be > or = to $N_{decks}$*$H_{DK}$**

**$C_{16}$ = Longitudinal strength criteria**

$$M := \begin{bmatrix} H_{MB} \\ N_{decks} \cdot H_{DK} \\ \frac{LWL}{15} \end{bmatrix} \qquad M = \begin{bmatrix} 25 \\ 36 \\ 33.4 \end{bmatrix} \bullet ft \qquad D_{10MIN} := \max(M) \qquad D_{10MIN} = 36 \bullet ft$$

$$D_{10} = D_{10x} \qquad D_{10x} := 37.0 \cdot ft \qquad > \text{or} = \qquad D_{10MIN} = 36 \bullet ft$$

**Calculate Cubic Number (CN) :**

$$CN := \frac{LWL \cdot B \cdot D_{10x}}{10^5 \cdot ft^3} \qquad CN = 10.01$$

**$FR_{6.1.3.3}$ = Prevent water from entering through skin of ship** **$DP_{6.1.3.3}$ = Exterior hull construction**

**Armor:** **(Spreadsheet Output)** $W_{164} := W_{x_5} \cdot lton$ $W_{164} = 37 \bullet lton$ **($FR_{6.1.3}$)**

**Sonar Dome/Appendages (structure): (Spreadsheet Output)** $W_{165} := W_{x_6} \cdot lton$ $W_{165} = 85.7 \bullet lton$ **($FR_{6.1.3}$)**

**Total Payload:** **(Spreadsheet Output)** $W_P := CUM_1 \cdot lton$ $W_P = 808.72 \bullet lton$ **(cumulative $FR_2$ - $FR_6$)**

**Outfit & Furnishings (600)**

**Hull Fittings:** $W_{OFH} := 3.6 \cdot lton$

**Personnel-related:** $W_{OFP} := .8 \cdot (N_T - 9.5) \cdot lton$ $W_{OFP} = 93.2 \bullet lton$

$$W_6 := W_{OFH} + W_{OFP} + W_{P600} \qquad W_6 = 104.54 \cdot lton$$

**Structure (100)**

**Hull Material: (OS: $C_{HMAT}$=1.0; HTS: $C_{HMAT}$=0.93)** $\quad C_{HMAT} := 0.93$

**Hull (110-140, 160, 190):** $W_{BH} := C_{HMAT} \cdot \left(1.68341 \cdot CN^2 + 167.1721 \cdot CN - 103.283\right) \cdot lto$

$$W_{BH} = 1617.07 \cdot lton$$

**Foundations:** $W_{180} := .0675 \cdot W_{BM} + .072 \cdot \left(W_3 + W_4 + W_5 + W_7\right) \qquad W_{180} = 137.34 \cdot lton$

$$W_1 := W_{BH} + W_{DH} + W_{171} + W_{180} + W_{165} + W_{164} \qquad W_1 = 2102.04 \cdot lton$$

**Hull Living Deck Area:** $A_{HAB} := 50 \cdot ft^2 \quad A_{HL} := \left(A_{HAB} + \frac{LWL}{100} \cdot ft\right) \cdot N_T - A_{DL} \qquad A_{HL} = 5581.26 \cdot ft^2$

**Hull Ship Functions:** $A_{HSF} := 2500 \cdot ft^2 \cdot CN \qquad A_{HSF} = 25024.95 \cdot ft^2$

**Clean Balast ($V_{BAL}$ = 0 for compensated system):** $V_{BAL} := 0 \cdot ft^3$

**Total Tankage:** $V_{TK} := V_F + V_{HF} + V_{LO} + V_W + V_{SEW} + V_{WASTE} + V_{BAL} \qquad V_{TK} = 114467.44 \cdot ft^3$

**Total Required Hull Area and Volume**

$$A_{HR} := A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + A_{HIEP} + A_{HIEe} \qquad A_{HR} = 43343.5 \cdot ft^2$$

$$V_{HR} := H_{DKh} \cdot A_{HR} \qquad V_{HR} = 390091.47 \cdot ft^3$$

**Total Required Area and Volume:**

$$A_{TR} := A_{HR} + A_{DR} \qquad A_{TR} = 58812.55 \cdot ft^2$$

$$V_{TR} := V_{DR} + V_{HR} \qquad V_{TR} = 529312.92 \cdot ft^3$$

*** Set available hull volume ($V_{HA}$) > or = to $V_{TR}$ - $V_D$ / Therefore, $A_{HA}$ also > or = to $A_{TR}$ - $A_{DA}$

$V_{HA} := V_{TR} - V_D$ $\quad\quad$ $V_{HA} = 373312.92 \cdot ft^3$

$A_{HA} := \dfrac{V_{HA}}{H_{DKh}}$ $\quad\quad$ $A_{HA} = 41479.21 \cdot ft^2$

Must satisfy $C_8$: Total available volume > Total required volume

and $C_9$: Total available arrangeable area > Total required arrangeable area

$V_{TA} := V_D + V_{HA}$ $\quad\quad$ $V_{TA} = 529312.92 \cdot ft^3$ > $V_{TR} = 529312.92 \cdot ft^3$

$A_{TA} := A_{DA} + A_{HA}$ $\quad\quad$ $A_{TA} = 58812.55 \cdot ft^2$ > $A_{TR} = 58812.55 \cdot ft^2$

$ERR_{VOL} := \dfrac{V_{TA} - V_{TR}}{V_{TR}}$ $\quad$ $ERR_{VOL} = 0$ $\quad\quad$ $ERR_{AREA} := \dfrac{A_{TA} - A_{TR}}{A_{TR}}$ $\quad$ $ERR_{AREA} = 0$

**Single Digit Weight Summary & Weight Balance:**

**Weight margin:**
**(Future Growth)** Required to satisfy $C_{10}$ = Incorporate design growth margins

$i1 := 1, 2..7$ $\quad\quad$ $W_{M24} := 0.10 \cdot \left(\sum_{i1} W_{i1}\right)$ $\quad\quad$ $W_{M24} = 427.39 \cdot lton$

**Lightship:** $W_{LS} := \sum_{i1} W_{i1} + W_{M24}$ $\quad\quad$ $W_{LS} = 4701.33 \cdot lton$

**Crew:** $W_{F10} := 236 \cdot lb \cdot N_E + 400 \cdot lb \cdot (N_O + 1)$ $\quad\quad$ $W_{F10} = 14.55 \cdot lton$

$W_T := W_{LS} + W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10}$ $\quad\quad$ $W_T = 7421.06 \cdot lton$

$FR_{6.2}$ = **Support total ship weight** $DP_{6.2}$ = **Displaced hull form volume**

**Must satisfy $C_3$: Full load displacement = Total weight**

$W_{FL} := W_T$ $\quad \Delta_{FL} := W_{FL}$ $\quad \Delta_{FL} = 7421.06 \cdot \text{lton}$

**Calculate Displacement to Length Ratio and compare to historical monohull design trends*:**

$$C_{\Delta L} := \frac{\Delta_{FL}}{\left(\frac{LWL}{100}\right)^3} \qquad C_{\Delta L} = 59.01 \cdot \frac{\text{lton}}{\text{ft}^3} \qquad \textbf{(45-65)}$$

* **Reference: "Hydrodynamics in Ship Design" by Saunders, SNAME 1957 Vol II (pg 466)**

**Weight Balance:** $ERR_{WEIGHT} := \frac{\Delta_{FL} - W_T}{W_T}$ $\quad ERR_{WEIGHT} = 0$

**Volume at LWL:** $V_{FL} := \Delta_{FL} \cdot 35 \cdot \frac{\text{ft}^3}{\text{lton}}$ $\quad V_{FL} = 259737 \cdot \text{ft}^3$

**Underwater Hull Volume:** $V_{HUW} := V_{FL}$

**Above water Volume:** $V_{HAW} := V_{HR} - V_{FL}$ $\quad V_{HAW} = 130354.47 \cdot \text{ft}^3$

$FR_{6.2.1}$ = **Maintain constant displacement** $DP_{6.2.1}$ = **Consistent loading philosophy**

$FR_{6.2.2}$ = **Maintain even transverse orientation (0 degree list)** $DP_{6.2.2}$ = **Centerline and symmetric (port/stbd) liquid tanks**

$FR_{6.2.3}$ = **Maintain even longitudinal orientation (0 trim)** $DP_{6.2.3}$ = **Longitudinal evenly spaced liquid tanks**

$FR_{6.3}$ = **Minimize total resistance**

$DP_{6.3}$ = **Hull form characteristics (coefficients of form)**

**Choose coefficient value within specified range*:**

* **Reference: "Hydrodynamics in Ship Design" by Saunders, SNAME 1957 Vol II (pg 466)**

$C_P := 0.610$ **(0.54 - 0.64)**

$C_W := .236 + .836 \cdot C_P$ $\quad C_W = 0.746$

$FR_{6.3.1}$ = **Minimize residuary resistance**

$DP_{6.3.1}$ = **Hull form factors**

$FR_{6.3.1.1}$ = **Minimize resistance caused by hull "fullness"**

$DP_{6.3.1.1}$ = **Maximum section coefficient ($C_X$)**

**Choose coefficient value within specified range*:**

* **Reference: "Hydrodynamics in Ship Design" by Saunders, SNAME 1957 Vol II (pg 469)**

$C_X := 0.850$ **(0.70 - 0.85)**

$C_P = 0.61$

$FR_{6.3.1.2}$ = **Minimize resistance caused by underwater hull volume**

$DP_{6.3.1.2}$ = **Volumetric coefficient ($C_V$)**

$$C_V := \frac{V_{FL}}{LWL^3} \qquad C_V = 0.0021$$

Constant draft required to satisfy $C_{11}$ = Always operate at DWL

**Calculate Draft (LWL) and compare with historical monohull design trends given in Tables 1 - 4:**

$$T := \frac{V_{FL}}{C_P \cdot C_X \cdot LWL \cdot B} \qquad T = 18.52 \bullet ft \qquad C_{BT} := \frac{B}{T} \qquad C_{BT} = 2.916 \quad \textbf{(2.8-3.7)}$$

**Must also satisfy sheer line criteria:**

$C_{17}$ = Keep deck edge above water at 25 degree heel / Therefore, $D_{10SL}$ must be < or = $D_{10x}$

$D_{10SL} := 0.21 \cdot B + T$ $\qquad D_{10SL} = 29.86 \bullet ft$ $\quad$ < or = $\quad D_{10x} = 37 \bullet ft$

If $D_{10SL} > D_{10x}$ ; $D_{10min} = D_{10SL}$
If $D_{10SL} < D_{10x}$ ; $D_{10min} = D_{10x}$

$$D_{0MIN} := 1.011827 \cdot T - 6.36215 \cdot \frac{10^{-6}}{ft} \cdot LWL^2 + 2.780649 \cdot 10^{-2} \cdot LWL + T \qquad D_{0MIN} = 49.59 \cdot ft$$

$$D_{20MIN} := .014 \cdot LWL \cdot \left(2.125 + 1.25 \cdot \frac{10^{-3}}{ft} \cdot LWL\right) + T \qquad D_{20MIN} = 37.81 \cdot ft$$

***** Update to indicate design desires complying with indicated results (minimum values):** $D_{10x} = 37 \cdot ft$

| | | | |
|---|---|---|---|
| $D_{0e} \equiv 49.59$ | $D_{10e} \equiv 37.00$ | $D_{20e} \equiv 37.81$ | $MASTe \equiv 100.00$ |
| $D_0 := D_{0e} \cdot ft$ | $D_{10} := D_{10e} \cdot ft$ | $D_{20} := D_{20e} \cdot ft$ | $MAST := MASTe \cdot ft$ |

***** If $D_{10}$ not equal $D_{10x}$, must modify $DP_{6.3.2}$ (i.e., set $D_{10x} = D_{10}$)**

**$FR_{6.3.2}$ = Minimize friction resistance** | **$DP_{6.3.2}$ = Submerged hull / water interaction**

**$FR_{6.3.2.1}$ = Produce viscous resistance forces (drag)** | **$DP_{6.3.2.1}$ = Relative motion between submerged hull and water**

**Use range of ship speeds for speed to length ratios ($R_i$), Reynold's numbers ($RN_i$), and ITTC friction ($RF_i$) :**

**CA's determine operating speed range:**

$i := 1 .. 7 \qquad V_i := i \cdot 5 \cdot knt$

**Ensure range includes $V_e$ and $V_S$ :** $\qquad V_4 := V_e \qquad V_6 := V_S$

$$V_4 = 20 \cdot knt \qquad V_6 = 28 \cdot knt$$

$$R_i := \frac{V_i}{\sqrt{LWL}} \qquad R_{N_i} := LWL \cdot \frac{V_i}{\nu_{SW}} \qquad C_{F_i} := \frac{.075}{\left(\log\left(R_{N_i}\right) - 2\right)^2}$$

$$V = \begin{bmatrix} 5 \\ 10 \\ 15 \\ 20 \\ 25 \\ 28 \\ 35 \end{bmatrix} \cdot knt \qquad R = \begin{bmatrix} 0.223 \\ 0.447 \\ 0.67 \\ 0.894 \\ 1.117 \\ 1.251 \\ 1.564 \end{bmatrix} \cdot \frac{knt}{\sqrt{ft}} \qquad R_N = \begin{bmatrix} 3.3 \cdot 10^8 \\ 6.61 \cdot 10^8 \\ 9.91 \cdot 10^8 \\ 1.32 \cdot 10^9 \\ 1.65 \cdot 10^9 \\ 1.85 \cdot 10^9 \\ 2.31 \cdot 10^9 \end{bmatrix} \qquad C_F = \begin{bmatrix} 0.0018 \\ 0.0016 \\ 0.0015 \\ 0.0015 \\ 0.0014 \\ 0.0014 \\ 0.0014 \end{bmatrix}$$

**$FR_{6.3.2.2}$ = Produce contact between hull and water** **$DP_{6.3.2.2}$ = Wetted surface area**

**Use Figure 7 with $C_P$ and $C_{BT}$ for TSS wetted surface coeficient:** $C_{STSS} := 2.536$

$C_P = 0.61 \qquad C_{BT} = 2.916$

$S_{TSS} := C_{STSS} \cdot (V_{FL})^{.5} \cdot LWL^{.5} \qquad S_{TSS} = 28929.11 \cdot ft^2$

**Specify or estimate actual ship surface area:** $S_S := S_{TSS}$

**Cumulative effects of above $FR_{6.3}$ design decisions:**

**Use Gertler* with $C_P$, $C_V$, $C_{BT}$, and $R_i$ to interpolate for $C_R$ and calcualte TSS resistance:**

$C_P = 0.61 \qquad C_V = 0.0021 \qquad C_{BT} = 2.916$

**$C_{BT}$=2.25** **$C_{BT}$=3.00** **$C_{BT}$=3.75**

$$R = \begin{bmatrix} 0.223 \\ 0.447 \\ 0.67 \\ 0.894 \\ 1.117 \\ 1.251 \\ 1.564 \end{bmatrix} \cdot \frac{knt}{\sqrt{ft}} \qquad C_{R2.25} := \begin{bmatrix} .00030 \\ .00030 \\ .00030 \\ .00063 \\ .00125 \\ .00259 \\ .00470 \end{bmatrix} \qquad C_{R3.00} := \begin{bmatrix} .00038 \\ .00038 \\ .00041 \\ .00087 \\ .00160 \\ .00279 \\ .00495 \end{bmatrix} \qquad C_{R3.75} := \begin{bmatrix} .00051 \\ .00051 \\ .00051 \\ .00086 \\ .00163 \\ .00295 \\ .00525 \end{bmatrix}$$

* **The Navy Department David W. Taylor Model Basin Report 806 of March 1954 - "A Reanalysis of the Original Test Data for the Taylor Standard Series" by Morton Goertler**
* **Reprinted in 1998 by the Society of Naval Architects and Marine Engineers (SNAME)**

**Form Factor:** $FF := \frac{4}{3} \cdot (C_{BT} - 3)$ $\qquad FF = -0.11$

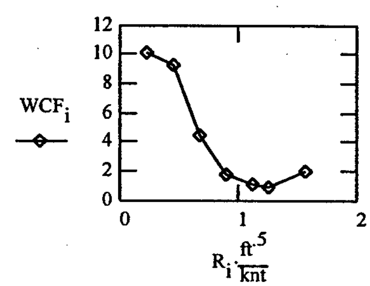
$$C_{RTSS_i} := C_{R3.00_i} + FF \cdot \left( \frac{C_{R3.75_i} - C_{R2.25_i}}{2} \right) + FF^2 \cdot \left( \frac{C_{R2.25_i} + C_{R3.75_i}}{2} - C_{R3.00_i} \right)$$

$$C_{RTSS} = \begin{bmatrix} 0.0004 \\ 0.0004 \\ 0.0004 \\ 0.0009 \\ 0.0016 \\ 0.0028 \\ 0.0049 \end{bmatrix} \qquad R_{RTSS_i} := .5 \cdot \left[ \rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot C_{RTSS_i} \right] \qquad R_{RTSS} = \begin{bmatrix} 757.77 \\ 3031.07 \\ 7368.08 \\ 28143.7 \\ 81040.59 \\ 178560.61 \\ 495575.8 \end{bmatrix} \circ lbf$$

**Worm Curve represents DD963 with bow mounted sonar dome:**

$$WCF_i := \left[ 67.31 \cdot \left( R_i \cdot \frac{ft^{.5}}{knt} \right)^5 - 327.80 \cdot \left( R_i \cdot \frac{ft^{.5}}{knt} \right)^4 + 604.33 \cdot \left( R_i \cdot \frac{ft^{.5}}{knt} \right)^3 - 508.17 \cdot \left( R_i \cdot \frac{ft^{.5}}{knt} \right)^2 \right] + 175.28 \cdot \left( R_i \cdot \frac{ft^{.5}}{knt} \right) - 9.5$$

$$R = \begin{bmatrix} 0.223 \\ 0.447 \\ 0.67 \\ 0.894 \\ 1.117 \\ 1.251 \\ 1.564 \end{bmatrix} \circ \frac{knt}{ft^{.5}} \qquad WCF = \begin{bmatrix} 10.16 \\ 9.32 \\ 4.52 \\ 1.82 \\ 1.14 \\ 0.95 \\ 2.03 \end{bmatrix}$$



$R_{R_i} := R_{RTSS_i} \cdot WCF_i$

$$R_R = \begin{bmatrix} 7702.32 \\ 28242.71 \\ 33301.83 \\ 51125.54 \\ 92639.5 \\ 168866.62 \\ 1 \cdot 10^6 \end{bmatrix} \cdot lbf$$

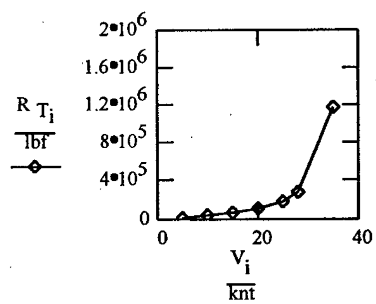
**Correlation Allowance:** $C_A := 0.0004$

$R_{F_i} := .5 \cdot \left[\rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot (C_A + C_{F_i})\right]$

$$R_F = \begin{bmatrix} 4450.53 \\ 16549.2 \\ 35752.71 \\ 61807.22 \\ 94546.25 \\ 117345.91 \\ 179612.45 \end{bmatrix} \cdot lbf$$

**Calculate Bare Hull Ship Resistance:** $R_{T_i} := R_{F_i} + R_{R_i}$

$$R_T = \begin{bmatrix} 12152.85 \\ 44791.91 \\ 69054.54 \\ 112932.76 \\ 187185.75 \\ 286212.53 \\ 1.18 \cdot 10^6 \end{bmatrix} \cdot lbf$$




$FR_{6.3.3}$ = **Minimize air resistance**

$DP_{6.3.3}$ = **Frontal area**

**Ship frontal area (+ 5% for masts, equipment, etc.):** $A_W := 1.05 \cdot B \cdot (D_{10} - T + 3 \cdot H_{DKd})$

$A_W = 2578.93 \cdot ft^2$

**Air Drag Coeficient:** $C_{AA} := 0.7$

**Must satisfy $C_4$ = Ensure intact stability (GM > 0 ft)**

**Must also satisfy $C_5$ = Maintain proper transverse dynamic stability (0.090 < GM/B < 0.122)**

**Stability**

**Payload VCG:** $VCG_P := CUM_3 \cdot ft$ $\quad VCG_P = 32.19 \cdot ft$ **(cumulative $FR_2$ - $FR_6$)**

**Variable Payload VCG:** $VCG_{VP} := CUM_4 \cdot ft$ $\quad VCG_{VP} = 29.71 \cdot ft$ **(cumulative $FR_3$ and $FR_6$**

**Calculate Light Ship Weight Group Moments:**

| **Weight** | **VCG** | | **Product** |
|---|---|---|---|
| $W_{BH} = 1617.07 \cdot lton$ | $VCG_1 := .527 \cdot D_{10}$ | $VCG_1 = 19.5 \cdot ft$ | $P_1 := W_{BH} \cdot VCG_1$ |
| $W_{DH} = 222.92 \cdot lton$ | $VCG_2 := D_{10} + 1.5 \cdot H_{DKd}$ | $VCG_2 = 50.5 \cdot ft$ | $P_2 := W_{DH} \cdot VCG_2$ |
| $W_{180} = 137.34 \cdot lton$ | $VCG_3 := .68 \cdot D_{10}$ | $VCG_3 = 25.16 \cdot ft$ | $P_3 := W_{180} \cdot VCG_3$ |
| $W_{171} = 2 \cdot lton$ | $VCG_4 := 2.65 \cdot D_{10}$ | $VCG_4 = 98.05 \cdot ft$ | $P_4 := W_{171} \cdot VCG_4$ |

$P_{100} := P_1 + P_2 + P_3 + P_4 \qquad VCG_{100} := \frac{P_{100}}{W_1} \qquad VCG_{100} = 22.09 \cdot ft$

| | | | |
|---|---|---|---|
| $W_{BM} = 361.38 \cdot lton$ | $VCG_5 := .5 \cdot D_{10}$ | $VCG_5 = 18.5 \cdot ft$ | $P_5 := W_{BM} \cdot VCG_5$ |
| $W_{ST} = 136.21 \cdot lton$ | $VCG_6 := 3.9 \cdot ft + .19 \cdot T$ | $VCG_6 = 7.42 \cdot ft$ | $P_6 := W_{ST} \cdot VCG_6$ |
| $W_{237} = 0 \cdot lton$ | $VCG_7 := VCG_{237}$ | $VCG_7 = 0 \cdot ft$ | $P_7 := W_{237} \cdot VCG_7$ |
| $W_{AUTO} = 1 \cdot lton$ | $VCG_8 := .5 \cdot D_{10}$ | $VCG_8 = 18.5 \cdot ft$ | $P_8 := W_{AUTO} \cdot VCG_8$ |

$P_{200} := P_5 + P_6 + P_7 + P_8 \qquad VCG_{200} := \frac{P_{200}}{W_2} \qquad VCG_{200} = 15.47 \cdot ft$

| | | | |
|---|---|---|---|
| $W_3 = 339.26 \cdot lton$ | $VCG_9 := .65 \cdot D_{10}$ | $VCG_9 = 24.05 \cdot ft$ | $P_9 := W_3 \cdot VCG_9$ |
| $W_{IC} = 43.8 \cdot lton$ | $VCG_{10} := D_{10}$ | $VCG_{10} = 37 \cdot ft$ | $P_{10} := W_{IC} \cdot VCG_{10}$ |
| $W_{CC} = 8.82 \cdot lton$ | $VCG_{11} := .5 \cdot D_{10}$ | $VCG_{11} = 18.5 \cdot ft$ | $P_{11} := W_{CC} \cdot VCG_{11}$ |

| | | | |
|---|---|---|---|
| $W_{498} = 87.9 \cdot lton$ | $VCG_{12} := VCG_{498}$ | $VCG_{12} = -1.2 \cdot ft$ | $P_{12} := W_{498} \cdot VCG_{12}$ |
| $W_{AUX} = 610.93 \cdot lton$ | $VCG_{13} := .9 \cdot (D_{10} - 7.4 \cdot ft)$ | $VCG_{13} = 26.64 \cdot ft$ | $P_{13} := W_{AUX} \cdot VCG_{13}$ |
| $W_{517} = 3.85 \cdot lton$ | $VCG_{14} := .5 \cdot H_{MB}$ | $VCG_{14} = 12.5 \cdot ft$ | $P_{14} := W_{517} \cdot VCG_{14}$ |
| $W_{OFH} = 3.6 \cdot lton$ | $VCG_{15} := .805 \cdot D_{10}$ | $VCG_{15} = 29.79 \cdot ft$ | $P_{15} := W_{OFH} \cdot VCG_{15}$ |
| $W_{OFP} = 93.2 \cdot lton$ | $VCG_{16} := 8 \cdot ft + .71 \cdot D_{10}$ | $VCG_{16} = 34.27 \cdot ft$ | $P_{16} := W_{OFP} \cdot VCG_{16}$ |

$ip := 1 .. 16$ $\quad P_{WG} := \sum_{ip} P_{ip} + W_P \cdot VCG_P - W_{VP} \cdot VCG_{VP}$ $\quad P_{WG} = 101133.94 \cdot lton \cdot ft$

**Light Ship KG**

$VCG_{LS} := \dfrac{P_{WG}}{\sum_{i1} W_{i1}}$ $\quad VCG_{LS} = 23.66 \cdot ft$ $\quad KG_{LS} := VCG_{LS}$ $\quad KG_{LS} = 23.66 \cdot ft$

**Calculate Variable Load Weight Group Moments:**

| **Weight** | **VCG** | | **Product** |
|---|---|---|---|
| $W_{F10} = 14.55 \cdot lton$ | $VCG_{17} := .746 \cdot D_{10}$ | $VCG_{17} = 27.6 \cdot ft$ | $P_{17} := W_{F10} \cdot VCG_{17}$ |
| $W_{F31} = 22.78 \cdot lton$ | $VCG_{18} := .55 \cdot D_{10}$ | $VCG_{18} = 20.35 \cdot ft$ | $P_{18} := W_{F31} \cdot VCG_{18}$ |
| $W_{F32} = 5.44 \cdot lton$ | $VCG_{19} := .65 \cdot D_{10}$ | $VCG_{19} = 24.05 \cdot ft$ | $P_{19}\ W_{F32} \cdot VCG_{19}$ |
| $W_{F41} = 2364.29 \cdot lton$ | $VCG_{20} := 7.5 \cdot ft$ | $VCG_{20} = 7.5 \cdot ft$ | $P_{20} := W_{F41} \cdot VCG_{20}$ |
| $W_{F42} = 63.8 \cdot lton$ | $VCG_{21} := 10. \cdot ft$ | $VCG_{21} = 10 \cdot ft$ | $P_{21} := W_{F42} \cdot VCG_{21}$ |
| $W_{F46} = 7.2 \cdot lton$ | $VCG_{22} := .35 \cdot D_{10}$ | $VCG_{22} = 12.95 \cdot ft$ | $P_{22} := W_{F46} \cdot VCG_{22}$ |
| $W_{F52} = 18.9 \cdot lton$ | $VCG_{23} := 7.5 \cdot ft$ | $VCG_{23} = 7.5 \cdot ft$ | $P_{23} := W_{F52} \cdot VCG_{23}$ |

$iL := 17 .. 23$ $\quad P_{WGL} := \sum_{iL} P_{iL} + W_{VP} \cdot VCG_{VP}$ $\quad P_{WGL} = 27983.04 \cdot lton \cdot ft$

$W_L := W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10}$ $\quad W_L = 2719.73 \cdot lton$

$VCG_L := \dfrac{P_{WGL}}{W_L}$ $\quad VCG_L = 10.29 \cdot ft$

**Calculate Ship Stability Characteristics:**

$KG_{MARG} := 0.5 \cdot ft$ **Required to satisfy $C_{10}$ = Incorporate design growth margins**

$KG := \frac{W_{LS} \cdot KG_{LS} + W_L \cdot VCG_L}{W_T} + KG_{MARG}$ $KG = 19.26 \cdot ft$ $C_{IT} := -.497 + 1.44 \cdot C_W$ $C_{IT} = 0.58$

$KB := \frac{T}{3} \cdot \left(2.5 - \frac{C_P \cdot C_X}{C_W}\right)$ $KB = 11.14 \cdot ft$ $BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}}$ $BM = 14.61 \cdot ft$

$GM := KB + BM - KG$ $GM = 6.49 \cdot ft$ **($GM > 0$ ft)**

$C_{GMB} := \frac{GM}{B}$ $C_{GMB} = 0.12$ **(0.09 - 0.122)**

***** If GM < 0 ft and/or GM/B not within limits, must alter DPs satisfying $FR_6$ and associated children (LWL, B, $C_p$, $C_x$, $D_{10}$, $D_{10}$, $D_{20}$) until achieve $C_4$ and $C_5$ compliance**

**- If stated DPs modified, must additionally verify/re-achieve $C_8$, $C_9$, and $C_{13}$ - $C_{17}$**

**Calculate roll period:**

$C := \frac{0.38 + 0.55}{2} \cdot ft^{-0.5}$ **(C = empirical constant = 0.38 - 0.55)** $T_{roll} := \frac{C \cdot B}{\sqrt{GM}} \cdot sec$ $T_{roll} = 9.86 \cdot sec$

**Must satisfy $C_6$: Installed propulsive power > Required propulsive power**

**- Verify propulsion system capable of achieving sustained speed**

**Determine total required propulsive power:**

**hull:** $P_{EBH_i} := R_{T_i} \cdot V_i$

$$P_{EBH} = \begin{bmatrix} 186.71 \\ 1376.33 \\ 3182.79 \\ 6940.23 \\ 14379.27 \\ 24624.69 \\ 127274.71 \end{bmatrix} \cdot hp$$

**Use Figure 8 or 9 with LWL for Appendage Drag Coeficient:** $C_{DAPP} := 2.75 \cdot \frac{hp \cdot 10^{-5}}{ft^2 \cdot knt^3}$

LWL = 501•ft

**appendage (propellers):** $P_{EAPPp_i} := \left[\left(LWL \cdot D_P\right) \cdot C_{DAPP}\right] \cdot \left(V_i\right)^3$

$$P_{EAPPp} = \begin{bmatrix} 32.72 \\ 261.77 \\ 883.48 \\ 2094.18 \\ 4090.2 \\ 5746.43 \\ 11223.5 \end{bmatrix} \circ hp$$

**appendage (sonar dome):** $P_{EAPPsd_i} := \left(.5 \cdot C_{SD} \cdot \rho_{SW} \cdot A_{SD}\right) \cdot \left(V_i\right)^3$

$$P_{EAPPsd} = \begin{bmatrix} 65.73 \\ 525.81 \\ 1774.6 \\ 4206.45 \\ 8215.73 \\ 11542.51 \\ 22543.96 \end{bmatrix} \circ hp$$

**total appendage:** $P_{EAPP_i} := P_{EAPPp_i} + P_{EAPPsd_i}$

$$P_{EAPP} = \begin{bmatrix} 98.45 \\ 787.58 \\ 2658.08 \\ 6300.63 \\ 12305.92 \\ 17288.94 \\ 33767.46 \end{bmatrix} \circ hp$$

**air:** $P_{EAA_i} := .5 \cdot C_{AA} \cdot A_W \cdot \rho_A \cdot \left(V_i\right)^3$

$$P_{EAA} = \begin{bmatrix} 2.36 \\ 18.87 \\ 63.67 \\ 150.93 \\ 294.79 \\ 414.16 \\ 808.9 \end{bmatrix} \circ hp$$

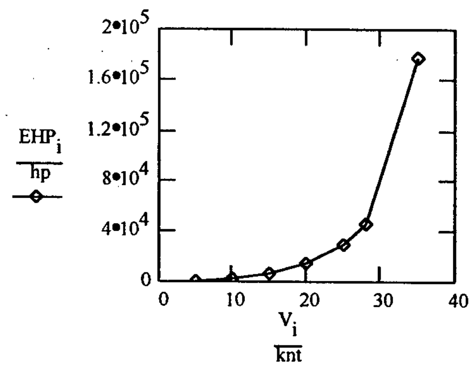
**Total Ship Effective Horsepower:**

$$P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i} \qquad P_{ET} = \begin{bmatrix} 287.52 \\ 2182.78 \\ 5904.54 \\ 13391.8 \\ 26979.98 \\ 42327.78 \\ 161851.07 \end{bmatrix} \cdot hp$$

**Power Margin Factor (margin for concept design = 10%):**
**Required to satisfy $C_{10}$ = Incorporate design growth margins**

$$PMF := 1.10 \qquad EHP_i := PMF \cdot P_{ET_i}$$

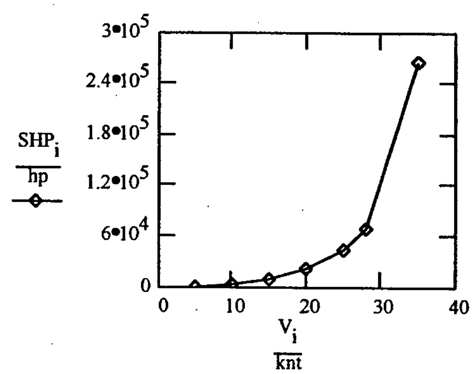
$$V = \begin{bmatrix} 5 \\ 10 \\ 15 \\ 20 \\ 25 \\ 28 \\ 35 \end{bmatrix} \cdot knt \qquad EHP = \begin{bmatrix} 316.27 \\ 2401.06 \\ 6494.99 \\ 14730.98 \\ 29677.98 \\ 46560.56 \\ 178036.17 \end{bmatrix} \cdot hp$$




**Required Shaft Horsepower:**

**Approximate Propulsive Coeficient (PC):** $PC := 0.67$ $\qquad SHP_i := \frac{EHP_i}{PC}$

$$SHP = \begin{bmatrix} 472.04 \\ 3583.67 \\ 9694.02 \\ 21986.53 \\ 44295.49 \\ 69493.37 \\ 265725.63 \end{bmatrix} \cdot hp$$




**Sustained Shaft Horsepower:** $P_S := SHP_6 \qquad P_S = 69493.37 \cdot hp$

**Installed Shaft Horsepower required to achieve sustained speed (Allows for fouling and sea state) :**

$P_{IREQ} := 1.25 \cdot P_S$ $\quad P_{IREQ} = 86866.71 \cdot hp$ $\quad P_I = 88270 \cdot hp$ $\quad$ **($P_I$ must be > $P_{IREQ}$)**

$$ERR_{POWER} := \frac{P_I - P_{IREQ}}{P_{IREQ}}$$

$ERR_{POWER} = 0.016$

***** If $P_I < P_{IREQ}$ ($ERR_{POWER} < 0$), must alter DPs satisfying $FR_6$ and associated children (LWL, B, $C_p$, $C_x$, $D_0$, $D_{10}$, $D_{20}$) until achieve $C_6$ compliance**

**- If stated DPs modified, must additionally verify/re-achieve $C_4$, $C_5$, $C_8$, $C_9$, and $C_{13}$ - $C_{17}$ compliance**

**Must satisfy $C_{17}$ = Carry adequate fuel to transit endurance range (E) at endurance speed ($V_e$), i.e. $E_{act}$ >=**

$P_e := SHP_4$ $\quad P_e = 21986.53 \cdot hp$ $\quad P_{eBAVG} := 1.1 \cdot \frac{P_e}{\eta}$ $\quad P_{eBAVG} = 24933.18 \cdot hp$

**Specific fuel rate for propulsion engines:** $\quad FR := 1.97 \cdot \frac{lb}{hp^{.85} \cdot hr} \cdot P_{eBAVG}^{-.15}$ $\quad FR = 0.431 \cdot \frac{lb}{hp \cdot hr}$

**(FR for GT = calc; FR for diesel = 0.327 lb/hphr; FR for ICR = 0.347 lb/hphr)**

**Margin for instrumentation and machinery differences, $f(P_e/P_I)$:** $f_1 := 1.04$

**Specified fuel rate:** $\quad FR_{SP} := f_1 \cdot FR$

**Average fuel rate allowing for plant deterioration:** $\quad FR_{AVG} := 1.05 \cdot FR_{SP}$ $\quad FR_{AVG} = 0.47 \cdot \frac{lb}{hp \cdot hr}$

$E_{act} := \frac{W_{BP} \cdot V_e}{(P_{eBAVG} \cdot FR_{AVG})}$ $\quad E_{act} = 7550.81 \cdot mile$ $\quad$ **> or =** $\quad E = 7500 \cdot mile$

$W_{BP} = 1980 \cdot lton$

***** If $E_{act}$ < E, increase $W_{BP}$ (weigth of burnable propulsion fuel)**

***** If $E_{act}$ >> E, decrease $W_{BP}$ (only if desired)**

**- If $W_{BP}$ modified, must additionally verify/re-achieve $C_4$ - $C_6$, $C_8$, $C_9$, and $C_{13}$ - $C_{17}$ compliance**

***** Strict adherence to Axiomatic Design principles does not allow modification of $W_{BP}$ ($DP_{5.8}$)**

# CONCEPT DESIGN PARAMETERS AND CONVERGENCE VERIFICATION:

**GROSS CHARACTERISTICS:** **Parameter/ratio ranges are ship specific - Compare with respective monohul design lanes**

| | | | | |
|---|---|---|---|---|
| $C_P = 0.61$ | **(0.54 - 0.64)** | $C_{\Delta L} = 59.01 \cdot \frac{lton}{ft^3}$ | **(45 - 65)** | $LWL = 501 \cdot ft$ |
| $C_X = 0.85$ | **(0.70 - .85)** | $C_V = 0.0021$ | | $B = 54 \cdot ft$ |
| $C_{BT} = 2.916$ | **(2.8 - 3.7)** | $C_{LB} = 9.278$ | **(7.5 - 10)** | $T = 18.52 \cdot ft$ |

**ENERGY BALANCE:**

| | | | |
|---|---|---|---|
| $V_S = 28 \cdot knt$ | $P_I = 88270 \cdot hp$ | $P_{IREQ} = 86866.71 \cdot hp$ | $ERR_{POWER} = 0.016$ |
| $V_e = 20 \cdot knt$ | $kW_G = 3000 \cdot kW$ | $kW_{GREQ} = 2812.65 \cdot kW$ | $ERR_{KW} = 0.067$ |
| $E_{act} = 7550.81 \cdot mile$ | | | |

**AREA/VOLUME BALANCE:**

| | | | |
|---|---|---|---|
| $A_{TR} = 58812.55 \cdot ft^2$ | $A_{HR} = 43343.5 \cdot ft^2$ | $A_{DR} = 15469.05 \cdot ft^2$ | |
| $A_{TA} = 58812.55 \cdot ft^2$ | $A_{HA} = 41479.21 \cdot ft^2$ | $A_{DA} = 17333.33 \cdot ft^2$ | $ERR_{AREA} = 0$ |
| $V_{TR} = 529312.92 \cdot ft^3$ | $V_{HR} = 390091.47 \cdot ft^3$ | $V_{DR} = 139221.45 \cdot ft^3$ | |
| $V_{TA} = 529312.92 \cdot ft^3$ | $V_{HA} = 373312.92 \cdot ft^3$ | $V_D = 156000 \cdot ft^3$ | $ERR_{VOL} = 0$ |
| $V_{MB} = 105300 \cdot ft^3$ | $V_{AUX} = 126360 \cdot ft^3$ | $V_{TK} = 114467.44 \cdot ft^3$ | $D_{10} = 37 \cdot ft$ |

**WEIGHT BALANCE:**

| | | | |
|---|---|---|---|
| $W_{FL} = 7421.06 \cdot lton$ | $W_T = 7421.06 \cdot lton$ | $ERR_{WEIGHT} = 0$ | |
| $W_1 = 2102.04 \cdot lton$ | $W_4 = 317.11 \cdot lton$ | $W_7 = 154.17 \cdot lton$ | $W_{LS} = 4701.33 \cdot lton$ |
| $W_2 = 498.58 \cdot lton$ | $W_5 = 758.23 \cdot lton$ | $W_{F41} = 2364.29 \cdot lton$ | $W_P = 808.72 \cdot lton$ |
| $W_3 = 339.26 \cdot lton$ | $W_6 = 104.54 \cdot lton$ | | |

**STABILITY/PAYLOAD:** $C_{GMB} = 0.12$ **(0.09 - 0.122)** $F_P := \frac{W_P}{W_{FL}}$ $F_P = 0.109$

# SIMPLIFIED COST MODEL

**DD13A-X**

**Definitions (units):** $Mdol := coul$ $\quad Bdol := 1000 \cdot Mdol$ $\quad Kdol := \frac{Mdol}{1000}$ $\quad dol := \frac{Kdol}{1000}$

$lton := 2240 \cdot lb$ $\quad hp := \frac{33000 \cdot ft \cdot lbf}{min}$

## 1. Single Digit Weight Summary:

$i1 := 100, 200 .. 700$

$W_{100} := W_1$ $\quad W_{400} := W_4$ $\quad W_{500} := W_5$ $\quad W_{F_{20}} := W_{F20}$ $\quad W_{F_{20}} = 222.77 \cdot lton$ #

$W_{200} := W_2$ $\quad W_{IC} = 43.8 \cdot lton$ $\quad W_{600} := W_6$ $\quad W_{F_{23}} := W_{F23}$ $\quad W_{F_{23}} = 12.73 \cdot lton$ #

$W_{300} := W_3$ $\quad W_{700} := W_7$ #

**Weight margin:** $W_M := W_{M24}$ $\quad W_M = 427.39 \cdot lton$ #

## 2. Additional Characteristics:

**Lightship:**

$W_{LS} := \sum_{i1} W_{i1} + W_M$ $\quad W_{LS} = 4701.33 \cdot lton$

**Costed Military Payload: (helo and helo fuel weight not included)**

$W_{MP} := \left[ \left( W_{400} + W_{700} \right) - W_{IC} \right] + W_{F_{20}} - W_{F_{23}}$ $\quad W_{MP} = 637.52 \cdot lton$

**Installed Propulsion Power:** $P_I = 88270 \cdot hp$ $\quad P_{SUM} := P_I$

**Manning: (crew + air detachment + staff)**

**Officers:** $N_{C_1} := N_O$ $\quad N_{C_1} = 15$

**CPO's:** $N_{C_2} := N_{CPO}$ $\quad N_{C_2} = 20$

**Crewmembers:** $N_{C_3} := N_{CR}$ $\quad N_{C_3} = 91$

**Ship Service Life:** $L_S := 30$ $\quad$ **Initial Operational Capability:** $Y_{IOC} := 2010$

**Total Ship Acquisition:** $N_S := 20$ $\quad$ **Production Rate (per year):** $R_P := 3$

## 3. Inflation:

**Base Year:** $Y_B := 2000$ $\quad iy := 1 .. Y_B - 1981$

**Average Inflation Rate (%):** $R_I := 3.0$ #
**(from 1981)**

$$F_I := \prod_{iy} \left(1 + \frac{R_I}{100}\right) \qquad F_I = 1.75$$

## 4. Lead Ship Cost:

*a. Lead Ship Cost - Shipbuilder Portion:*

**SWBS costs: (See Enclosure 1 for $K_N$ factors); includes escalation estimate**

**Structure** $K_{N1} := \frac{.55 \cdot Mdol}{lton^{.772}}$ $\quad C_{L_{100}} := .03395 \cdot F_I \cdot K_{N1} \cdot (W_{100})^{.772}$ $\quad C_{L_{100}} = 12.03 \cdot Mdol$

**+ Propulsion** $K_{N2} := \frac{1.2 \cdot Mdol}{hp^{.808}}$ $\quad C_{L_{201}} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{SUM}^{.808}$ $\quad C_{L_{201}} = 38.8 \cdot Mdol$

$C_{L_{202}} = C_{automation}$, hardware + software $\quad C_{L_{202}} := 0.5 \cdot Mdol$

$C_{L_{200}} := C_{L_{201}} + C_{L_{202}}$ $\quad C_{L_{200}} = 39.3 \cdot Mdol$

**+ Electric** $K_{N3} := \frac{1.0 \cdot Mdol}{lton^{.91}}$ $\quad C_{L_{300}} := .07505 \cdot F_I \cdot K_{N3} \cdot (W_{300})^{.91}$ $\quad C_{L_{300}} = 26.43 \cdot Mdol$

**+ Command, Control, Surveillance**

$K_{N4} := \frac{2.0 \cdot Mdol}{lton^{.617}}$ $\quad C_{L_{400}} := .10857 \cdot F_I \cdot K_{N4} \cdot (W_{400})^{.617}$ $\quad C_{L_{400}} = 13.3 \cdot Mdol$

**(less payload GFM cost)**

**+ Auxiliary** $K_{N5} := \frac{1.5 \cdot Mdol}{lton^{.782}}$ $\quad C_{L_{500}} := .09487 \cdot F_I \cdot K_{N5} \cdot (W_{500})^{.782}$ $\quad C_{L_{500}} = 44.58 \cdot Mdol$

**+ Outfit** $K_{N6} := \frac{1.0 \cdot Mdol}{lton^{.784}}$ $\quad C_{L_{600}} := .09859 \cdot F_I \cdot K_{N6} \cdot (W_{600})^{.784}$ $\quad C_{L_{600}} = 6.62 \cdot Mdol$

+ **Armament** $K_{N7} := \frac{1.0 \cdot Mdol}{lton^{.987}}$ $C_{L_{700}} := .00838 \cdot F_I \cdot K_{N7} \cdot \left(W_{700}\right)^{.987}$ $C_{L_{700}} = 2.12 \cdot Mdol$

**(Less payload GFM cost)**

+ **Margin Cost:**

$$C_{LM} := \frac{W_M}{\left(W_{LS} - W_M\right)} \cdot \left(\sum_{i1} C_{L_{i1}}\right) \qquad C_{LM} = 14.44 \cdot Mdol$$

+ **Integration/Engineering: (Lead ship includes detail design engineering + plans for class)**

$$K_{N8} := \frac{10. \cdot Mdol}{Mdol^{1.099}} \qquad C_{L_{801}} := .034 \cdot K_{N8} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{1.099} \qquad C_{L_{801}} = 89.18 \cdot Mdol$$

$C_{L_{802}} = C_{automation}$, testing and evaluation $\qquad C_{L_{802}} := 5.0 \cdot Mdol$

$$C_{L_{800}} := C_{L_{801}} + C_{L_{802}} \qquad C_{L_{800}} = 94.18 \cdot Mdol$$

+ **Ship Assembly + Support: (Lead ship includes all tooling, jigs, special facilities for class)**

$$K_{N9} := \frac{2.0 \cdot Mdol}{(Mdol)^{.839}} \qquad C_{L_{900}} := .135 \cdot K_{N9} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{.839} \qquad C_{L_{900}} = 18.96 \cdot Mdol$$

***a. Lead Ship Cost - Shipbuilder Portion (continued):***

= **Total Lead Ship Construction Cost: (BCC):**

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_{800}} + C_{L_{900}} + C_{LM} \qquad C_{LCC} = 271.95 \cdot Mdol$$

+ **Profit:**

$F_P := .10$ $\qquad C_{LP} := F_P \cdot C_{LCC}$ $\qquad C_{LP} = 27.2 \cdot Mdol$ #

= **Lead Ship Price:**

$$P_L := C_{LCC} + C_{LP} \qquad P_L = 299.15 \cdot Mdol$$

+ **Change Orders:**

$C_{LCORD} := .12 \cdot P_L$ $\qquad C_{LCORD} = 35.9 \cdot Mdol$ #

= ***<u>Total Shipbuilder Portion:</u>***

$C_{SB} := P_L + C_{LCORD}$ $\qquad C_{SB} = 335.05 \cdot Mdol$

## *b. Lead Ship Cost - Government Portion*

**Other support:** $\qquad C_{LOTH} := .025 \cdot P_L \qquad C_{LOTH} = 7.48 \cdot Mdol$ #

**+ Program Manager's Growth:** $\qquad C_{LPMG} := .1 \cdot P_L \qquad C_{LPMG} = 29.91 \cdot Mdol$ #

**+ Ordnance and Electrical GFE:**
**(Military Payload GFE)**

$$C_{LMPG} := \left(.318 \cdot \frac{Mdol}{lton} \cdot W_{MP} + N_{HELO} \cdot 18.71 \cdot Mdol\right) \cdot F_I$$

$C_{LMPG} = 421.1 \cdot Mdol$ **(or incl actual cost if known)**

**+ HM&E GFE (boats, IC):** $\qquad C_{LHMEG} := .02 \cdot P_L \qquad C_{LHMEG} = 5.98 \cdot Mdol$

**+ Outfittimg Cost :** $\qquad C_{LOUT} := .04 \cdot P_L \qquad C_{LOUT} = 11.97 \cdot Mdol$

= ***<u>Total Government Portion:</u>***

$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT} \qquad C_{LGOV} = 476.45 \cdot Mdol$

## *c. Total Lead Ship End Cost:* ***(Must always be less than appropriation)***

*** *<u>Total End Cost:</u>*** $\qquad C_{LEND} := C_{SB} + C_{LGOV} \qquad C_{LEND} = 811.49 \cdot Mdol$

## d. Total Lead Ship Acquisition Cost:

**+ Post-Delivery Cost (PSA):** $\qquad C_{LPDEL} := .05 \cdot P_L \qquad C_{LPDEL} = 14.96 \cdot Mdol$ #

= **<u>Total Lead Ship Acquisition Cost:</u>** $\quad C_{LA} := C_{LEND} + C_{LPDEL} \qquad C_{LA} = 826.45 \cdot Mdol$

## <u>5. Follow-Ship Cost:</u>

**Learning Rate/Factor:** $\qquad R_L := .97 \qquad F := 2 \cdot R_L - 1 \qquad F = 0.94$ #

*a. Follow Ship Cost - Shipbuilder Portion*

$$C_{F_{i1}} := F \cdot \frac{C_{L_{i1}}}{coul} \qquad C_{FM} := F \cdot C_{LM} \qquad C_{FM} = 13.57 \cdot Mdol$$

$$C_{F_{800}} := \frac{.104}{Mdol^{1.099}} \cdot \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{1.099} \qquad C_{F_{800}} \cdot coul = 27.28 \cdot Mdol$$

$$C_{F_{900}} := F \cdot \frac{C_{L_{900}}}{coul} \qquad C_{F_{900}} = 17.83$$

| $\frac{C_{F_{i1}} \cdot coul}{Mdol}$ |
|---|
| 11.31 |
| 36.94 |
| 24.84 |
| 12.5 |
| 41.9 |
| 6.22 |
| 1.99 |

**Total Follow Ship Construction Cost: (BCC)**

$$C_{FCC} := \sum_{i1} \frac{C_{F_{i1}} \cdot Mdol}{coul} + \frac{C_{F_{800}} \cdot coul}{Mdol} + C_{F_{900}} + \frac{C_{FM}}{Mdol} \qquad C_{FCC} \cdot coul = 194.39 \cdot Mdol$$

**+ Profit:**

$F_P := .1 \qquad C_{FP} := F_P \cdot C_{FCC} \cdot coul \qquad C_{FP} = 19.44 \cdot Mdol$ #

= **Follow Ship Price:**

$P_F := C_{FCC} \cdot coul + C_{FP} \qquad P_F = 213.83 \cdot Mdol$

**+ Change Orders:**

$C_{FCORD} := .08 \cdot P_L \qquad C_{FCORD} = 23.93 \cdot Mdol$ #

= **Total Follow Ship Shipbuilder Portion:**

$C_{FSB} := P_F + C_{FCORD} \qquad C_{FSB} = 237.76 \cdot Mdol$

## *b. Follow Ship Cost - Government Portion*

**Other support:** $C_{FOTH} := .025 \cdot P_F \qquad C_{FOTH} = 5.35 \cdot Mdol$ #

**+ Program Manager's Growth:** $C_{FPMG} := .05 \cdot P_F$ #

number of helo's: $N_{HELO} = 2$

+ **Ordnance and Electrical GFE: (Military Payload GFE)**

$$C_{FMPG} := \left(.3 \cdot \frac{Mdol}{lton} \cdot W_{MP} + 18.710 \cdot Mdol \cdot N_{HELO}\right) \cdot F_I$$

$$C_{FMPG} = 400.98 \cdot Mdol$$

+ **HM&E GFE (boats, IC):** $C_{FHMEG} := .02 \cdot P_F$ $C_{FHMEG} = 4.28 \cdot Mdol$ #

+ **Outfittimg Cost:** $C_{FOUT} := .04 \cdot P_F$ $C_{FOUT} = 8.55 \cdot Mdol$ #

= ***Total Follow Ship Government Cost:***

$$C_{FGOV} := C_{FOTH} + C_{FPMG} + C_{FMPG} + C_{FHMEG} + C_{FOUT} \qquad C_{FGOV} = 429.85 \cdot Mdol$$

## c. Total Follow Ship End Cost:
## (Must always be less than SCN appropriation)

* ***Total Follow Ship End Cost:***

$$C_{FEND} := C_{FSB} + C_{FGOV} \qquad C_{FEND} = 667.61 \cdot Mdol$$

## d. Total Follow Ship Acquisition Cost:

+ **Post-Delivery Cost (PSA):** $C_{FPDEL} := .05 \cdot P_F$ $C_{FPDEL} = 10.69 \cdot Mdol$ #

= ***Total Follow Ship Acquisition Cost:*** $C_{FA} := C_{FEND} + C_{FPDEL}$ $C_{FA} = 678.3 \cdot Mdol$

## AVERAGE SHIP ACQUISITION COST:

$$C_{AV} := \frac{\frac{C_{FA} - C_{FMPG}}{F} \cdot \left(N_S - 1\right)^{\frac{\ln(2 \cdot R_L)}{\ln(2)}} + \left(N_S - 1\right) \cdot C_{FMPG} + C_{LA}}{N_S} \qquad C_{AV} = 668.51 \cdot Mdol$$

## 6. Life Cycle Cost:

*a. Research and development*

**Ship design and development:**

$$C_{SDD} := 1.1 \cdot \left( .571 \cdot \frac{C_{FSB}}{F} + .072 \cdot C_{LMPG} \right) \qquad C_{SDD} = 192.22 \circ Mdol \qquad \#$$

**+ Ship test and evaluation**

$$C_{STE} := 1.2 \cdot \left( .499 \cdot \frac{C_{FSB}}{F} + .647 \cdot C_{LMPG} \right) \qquad C_{STE} = 478.4 \circ Mdol \qquad \#$$

= ***Total Ship R&D Cost:***

$$C_{RD} := C_{SDD} + C_{STE} \qquad C_{RD} = 670.62 \circ Mdol$$

***b) Investment (less base facilities, unrep, etc)***

**Ships:**

$$C_{SPE} := \frac{C_{FA}}{F} \cdot N_S^{\frac{\ln(2 \cdot R_L)}{\ln(2)}} \qquad C_{SPE} = 12.65 \circ Bdol$$

**average ship cost:** $C_{AVG} := \frac{C_{SPE}}{N_S}$ $\qquad C_{AVG} = 632.59 \circ Mdol$

**+ Support Equipment (shore-based)**

**ship:** $C_{SSE} := .15 \cdot C_{SPE}$ $\qquad C_{SSE} = 1.9 \circ Bdol$ $\qquad \#$

**+ Spares and repair parts (shore supply)**

**ship:** $C_{ISS} := .1 \cdot C_{SPE}$ $\qquad C_{ISS} = 1.27 \circ Bdol$ $\qquad \#$

## = Total Investment Cost:

$$C_{INV} := C_{SPE} + C_{SSE} + C_{ISS}$$

$$C_{INV} = 15.81 \circ Bdol$$

## *c) Operations and Support*

**Personnel (Pay and Allowances)**

$$C_{PAY} := F_I \cdot \left[ .026184 \cdot N_{C_1} + .01151 \cdot \left( N_{C_2} + N_{C_3} \right) \right] \cdot N_S \cdot L_S \cdot Mdol \qquad C_{PAY} = 1.76 \circ Bdol$$

$$C_{TAD} := F_I \cdot \left(N_{C_1} + N_{C_2} + N_{C_3}\right) \cdot N_S \cdot L_S \cdot 2.6 \cdot 10^{-6} \cdot Mdol \qquad C_{TAD} = 0.34 \circ Mdol$$

$$C_{PERS} := C_{PAY} + C_{TAD} \qquad C_{PERS} = 1.76 \circ Bdol$$

**+ Operations:**

**Operating hours/year:** $H := 2500 \cdot hr$ #

$$C_{OPS} := N_S \cdot L_S \cdot \left[ F_I \cdot Kdol \cdot \left[ 188. + 2.232 \cdot \left(N_{C_1} + N_{C_2} + N_{C_3}\right) - \frac{H}{26.9 \cdot hr} \right] + \frac{C_{AVG}}{769.2} + \frac{C_{FMPG}}{196} \right]$$

$$C_{OPS} = 2.12 \circ Bdol$$

**+ Maintenance**

$$C_{MTC} := N_S \cdot L_S \cdot \left[ F_I \cdot Kdol \cdot \left[ 2967 + 4.814 \cdot \left(N_{C_1} + N_{C_2} + N_{C_3}\right) - \frac{H}{3.05 \cdot hr} \right] + \frac{C_{AVG}}{156.25} \right]$$

$$C_{MTC} = 5.33 \circ Bdol$$

**+ Energy (Assumes all operation at Endurance Power with no electric load)**

**Fuel Rate:** $FR \cdot P_{eBAVG} = 4.8 \circ \frac{lton}{hr}$ $\qquad C_{FUEL} := .9 \cdot \frac{dol}{gal}$ #

$$C_{EGY} := N_S \cdot L_S \cdot C_{FUEL} \cdot \frac{H}{6.8 \cdot \frac{lb}{gal}} \cdot FR \cdot P_{eBAVG} \qquad C_{EGY} = 2.14 \circ Bdol$$

**+ Replenishment Spares**

$$C_{REP} := C_{ISS} \cdot \frac{L_S - 4}{4} \qquad C_{REP} = 8.22 \circ Bdol$$

**+ Major Support (COH, ROH):**

$$C_{MSP} := N_S \cdot L_S \cdot \left[ 698. + 5.988 \cdot \left(N_{C_1} + N_{C_2} + N_{C_3}\right) - \frac{H}{10.36 \cdot hr} \right] \cdot Kdol \cdot F_I + .0022 \cdot C_{AVG}$$

$$C_{MSP} = 1.28 \circ Bdol$$

= ***<u>Total Operation and Support Cost:</u>*** $C_{OAS} := C_{PERS} + C_{OPS} + C_{MTC} + C_{EGY} + C_{REP} + C_{MS}$

$$C_{OAS} = 20.84 \circ Bdol$$

## d. Residual Value:

$$RES := .5 \cdot C_{SPE} \cdot \left(1 - \frac{2}{L_S}\right)^{L_S} \qquad RES = 0.8 \cdot Bdol$$

## e. Total Program

* ***Total Life Cycle Cost (Undiscounted):***

$$C_{LIFE} := C_{RD} + C_{INV} + C_{OAS} - RES$$

$$C_{LIFE} = 36.52 \cdot Bdol$$

# 7. Discounted Life Cycle Cost:

**Discount Rate:** $R_D := 0.10$ #

***a. Discounted R&D:***

**Length of R&D Phase:** $L_{RD} := 13$ #

**end:** $E_{RD} := Y_{IOC} + 2 - Y_B \qquad E_{RD} = 12$ **(normalized to base year)**

**start:** $B_{RD} := E_{RD} - L_{RD} + 1 \qquad B_{RD} = 0$

$$F_{DRD} := \frac{\displaystyle\sum_{y = B_{RD}}^{E_{RD}} \frac{1}{(1 + R_D)^y}}{L_{RD}} \qquad F_{DRD} = 0.6$$

$$C_{DRD} := F_{DRD} \cdot C_{RD} \qquad C_{DRD} = 403.08 \cdot Mdol$$

***b. Discounted Investment:***

**start:** $B_{INV} := E_{RD} + 1$

**end:** $E_{INV} := B_{INV} + \mathrm{ceil}\left(\left(\frac{N_S - 1}{R_P}\right)\right) \qquad E_{INV} = 20$

$$L_{INV} := E_{INV} - B_{INV} + 1 \qquad L_{INV} = 8$$

$$F_{DINV} := \frac{\displaystyle\sum_{y = B_{INV}}^{E_{INV}} \frac{1}{(1 + R_D)^y}}{L_{INV}} \qquad F_{DINV} = 0.21$$

$$C_{DINV} := F_{DINV} \cdot C_{INV} \qquad C_{DINV} = 3.36 \cdot Bdol$$

***c. Discounted O&S:***

**start:** $B_{OAS} := E_{INV} + 1 \qquad B_{OAS} = 21$

**end:** $E_{OAS} := B_{OAS} + L_S - 1 \qquad E_{OAS} = 50$

$$L_{OAS} := E_{OAS} - B_{OAS} + 1 \qquad L_{OAS} = 30$$

$$F_{DOAS} := \frac{\displaystyle\sum_{y = B_{OAS}}^{E_{OAS}} \frac{1}{\left(1 + R_D\right)^y}}{L_{OAS}} \qquad F_{DOAS} = 0.05$$

$$C_{DOAS} := F_{DOAS} \cdot C_{OAS} \qquad C_{DOAS} = 0.97 \cdot Bdol$$

## *d. Discounted Residual Value:*

$$RES_D := RES \cdot \left(\frac{1}{1 + R_D}\right)^{E_{OAS}+1} \qquad RES_D = 6.18 \cdot Mdol$$

## *e. Total Discounted Life Cycle Cost:*

$$C_{DLIFE} := C_{DRD} + C_{DINV} + C_{DOAS} - RES_D \qquad C_{DLIFE} = 4.73 \cdot Bdol$$

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